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Adaptive Fuzzy Fault-Tolerant Control for a Class of Nonlinear Systems under Actuator Faults: Application to an Inverted Pendulum Abdelhamid Bounemeur a,1,*, Mohamed Chemachema a,2 a,1 Dept. of electronics, Faculty of Technology, University of Constantine, Constantine, Algeria 1 hamidsie4@gmail.com; 2 m_chemachema@yahoo.fr * Corresponding Author ARTICLE INFO _ _ABSTRACT _ _ Article history Received 11 April 2021 Revised 05 May 2021 Accepted 08 May 2021 _ _This work investigates a fuzzy direct adaptive fuzzy fault-tolerant Control (FFTC) for a class of perturbed single input single output (SISO) uncertain nonlinear systems. The designed controller consists of two sub-controllers.

One is an adaptive unit, and the other is a robust unit, whereas the adaptive unit is devoted to getting rid of the dynamic uncertainties along with the actuator faults, while the second one is developed to deal with fuzzy approximation errors and exogenous disturbances. It is proved that the proposed approach ensures a good tracking performance against faults occurring, uncertainties, and exogenous disturbances, and the stability study of the closed-loop is proved regarding the Lyapunov direct method in order to prove that all signals remain bounded. Simulation results are presented to illustrate the accuracy of the proposed technique. This is an open access article under the CC–BY-SA license.

/ _ _ Keywords Adaptive fuzzy control; Fault-tolerant control; Lyapunov stability; Inverted Pendulum; Actuator faults _ _ _ _Introduction Recently, the Adaptive control technique has witnessed much attention in control theory society due to its ability to deal with system uncertain or unknown dynamics [1]-[9]. Generally speaking, universal approximator such as neural networks (NNs) and fuzzy logic systems (FLSs) tools was a good solution to overcome system uncertainty [10] [11], or fuzzy systems as universal approximator [1]-[6].

Various Fuzzy adaptive techniques have been developed in the literature classified from SISO to MIMO linear and nonlinear systems. In the design stage of fuzzy adaptive control law, direct and indirect approaches have been studied. In the direct, one controller consists to approximate the ideal control law with the help of a fuzzy system (see Refs. [12] [13] [14] [1]-[9]). However, the indirect resides on the approximation of the uncertain nonlinear system using fuzzy systems and based on these approximations. A general adaptive controller is built [1-5] [12] [13] [16]-[19].

On the other side, the adaptive technique was integrated with fault-tolerant control approach to deal with actuator and sensor failures. Practically, sensor and/or actuator faults seem unavoidable separately or collectively due to their importance. If an actuator or sensor faults occurring during the system operation, this can lead to a catastrophic behavior and also drive the system to instability. Authors in [1] have investigated an adaptive fuzzy fault-tolerant control scheme for a class of nonlinear systems with simultaneous actuator and sensor failures.

A combination method based on fuzzy systems (FSs) and backstepping approach allowed the online estimation of the adaptive parameters and guaranteed the boundedness of all signals in the closed-loop system, while in [4], an active fault-tolerant control technique has been proposed for a class of second-order nonlinear system subjected to state-dependent actuator faults with the presence of unknown control gain sign and external disturbances. In [20], adaptive fault-tolerant control is applied on a flexible spacecraft with state-dependent actuator failures using simple linear sets of system states and errors combination.

In [21], the authors proposed a dynamic surface-based control approach using the Nussbaum-type function for attitude stabilization of a spacecraft under actuator saturation. More results can be found in [22], where an active fault-tolerant control scheme has been developed for a class of MIMO nonlinear systems with sensor failures based on dynamic surface control (DSC). Based on the aforementioned works, a fuzzy adaptive fault-tolerant control strategy is proposed for a class on the nonlinear system under the presence of actuator faults, exogenous disturbance, and uncertainties.

A modified controller with new adaptive algorithms are designed and the upper and lower bounds of the control gain sign (CGS). An additional robust control term is added to circumvent the problem of approximation errors and mollify the tracking curves. The main contributions of the proposed controller are summarized below: The proposed controller, along with a robust term, is superior to the controller performance in [14].

The actuator faults model is time-varying parameters with bias, drift, loss of accuracy, and loss of effectiveness, which make the controller affordable against large faults scale. The exogenous disturbance is handled theoretically instead of approximation.

The remainder of this paper is designed as follows: Problem formulation along with the studied class is first described, followed by a brief description of the universal approximation, i.e., fuzzy logic systems. Then, the proposed direct adaptive fuzzy fault-tolerant control scheme is presented with the corresponding adaptive laws and the stability analysis using Lyapunov methodology. To test the accuracy of the proposed technique, a simulation example on the dynamic model of an inverted pendulum is performed. Finally, some conclusions and general comments are given.

Problem Formulation Consider the class of SISO nonlinear systems without faults (faults free) that can be written under the following equations [3] [6] _ ?? 1 = ?? 2 ? ?? ?? =?? ?? 1 , ?? 2 ,… ?? ?? +?? ?? 1 , ?? 2 ,… ?? ?? ??+?? ?? ??= ?? 1 _(1) _ _Which can be concise and written as _ ?? (??) =?? ?? +?? ?? ??+?? ?? ??= ?? 1 _(2) _ _where ??= [?? 1 ,…, ?? ??] ?? ? R ?? , is the vector of the system;???R is the scalar control input; ???R is the scalar system output; ?? ?? and ?? ?? are unknown smooth nonlinear functions; ??(??) is considered as an exogenous disturbance. In respect to the dynamic of the system (2), the following assumptions will be made: Assumption 1: the order ?? of the system is known.

Assumption 2: the state vector is available for measurement. Assumption 3: there exists an unknown continuous positive function ??(??) as: ?? (??) =??(??) In this paper, actuator faults are considered with additive and multiplicative models, as shown in Table 1 (see in [1]). Table 1. Actuators Faults Actuators _Faults Kinds _Conditions _Faults Names _ _??(??) _?? ?? +?? _ ?? ?? =0,?? ?? ?? ?0 _???????? (???????? ???? ??????????) _ _ _?? ?? +?? ?? _ ?? ?? =???? ,0<??«1 ?????? ?????? ??= ?? ?? _?????????? _ _ _?? ?? +?? ?? _ ?? ?? < ?? 0 , ?? ?? ?0 ?????? ?????? ??= ?? ?? _???????? ???? ???????????????? _ _ _?? ?? ?? ?? _0< ?? =??(??)=1?????? ?????? ??= ?? ?? _???????? ???? ????????????????????????? _ _where ?? ?? denotes the time instant of failure of the ??th sensor/actuator and ?? denotes its accuracy coefficient such that ????[- ?? 0 , ?? 0], where ?? 0 >0.

Also ????[?? ,1], where ?? >0 denotes the minimum sensor and actuator effectiveness, in which ?? and ?? are slowly varying respectively within [- ?? 0 , ?? 0] and [?? ,1]. Regarding the faults given in Table 1, then the faulty actuator can be described by the following compact form _ ?? ?? ?? =?? ?? ?? ?? +?? ?? _(2a) _ _The system described in (2a) will take the following form _ ?? (??) =?? ?? +?? ?? ?? ?? ?? ?? +?? ?? +??(??) ??= ?? 1 _(2b) _ _Which can be rewritten in the following compact form _ ?? (??) =?? ?? +?? ?? ?? ?? + ?? ?? ??,?? +??(??) ??= ?? 1 _(2c) _ _Where ?? ?? ??,?? =??(??)((??-1)??(??)+?? ??) The objective is to design an adaptive fuzzy controller for system (2c) under actuator faults, exogenous disturbances, and uncertainties such that the system output ??(??) follows a desired trajectory ?? ?? (??) while all signals in the closed-loop system remain bounded.

Regarding the development of the control law, the following assumption should also be made: Assumption 4: the desired trajectory ?? ?? (??) and its time derivatives ?? ?? (??) , ??=1,…,?? are smooth and bounded. Assumption 5: the control gain ??(??) is different to zero, and its sign is known we suppose that ??(??)> ?? >0 with ?? is unknown constant Assumption 6: the approximation error is bounded as ??(??) = ?? ?? Now, let us define the tracking error vector as _??= ??, ?? ,…; ?? ??-1 ?? ? R ?? _(3) _ _With _?? ?? = ?? ?? ?? -?? ?? _(4) _ _ _ ?? (??) = ?? ?? (??) - ?? ?? _(5) _ _ _ ?? (??) = ?? ?? (??) -?? ?? -?? ?? ??- ?? ?? ??,?? -??(??) _(6) _ _If the functions (?? ?? ,?? ?? , ??(??)and ??(??)) are known, our control objective is reached, let consider the ideal control law: _??= ?? * = ??-?? ?? - ?? ?? ??,?? -??(??) ??(??) + ?? ?? 2 ?? ?? 2 ?? ?? ???? ?? ?? ???? _(7) _ _where ?? is the solution of the Lyapunov-like equation, and it will be designed later, and, _ ?? (??) = ?? ?? (??) -?? ?? -?? ?? ??-?? ?? - ?? ?? ??,?? -??(??) ?? ?? + ?? ?? 2 ?? ?? 2 ?? ?? ???? ?? ?? ???? _(8) _ _ _ ?? (??) =- ?? ?? ??-?? ?? ?? ?? 2 ?? ?? 2 ?? ?? ???? ?? ?? ???? _(9) _ _The dynamic error can be further written as _ ?? =????+?? -?? ?? ??(??) 2 ??(??) 2 ?? ?? ???? ?? ?? ???? _(10) _ _where ??= 0 1 ? 0 ? ? ? 0 0 - ?? ?? 0 - ?? ??-1 ? 1 … - ?? ?? ??= 0 ? 0 1 Define the Lyapunov-like equation as _??= 1 2??(??) ?? ?? ???? _(11) _ _where ?? define a symmetric positive definite matrix satisfying the Lyapunov-like equation _ ?? ?? ??+????=-?? _(12) _ _Where ??>0.

Taking the time-derivative of the Lyapunov-like equation along with the error dynamic (10), we can reach the following result _ ?? =- 1 2?? ?? ?? ?? ????+ ?? ?? ???? ?? ?? -1 -?? ?? ?? ?? 2 ?? ?? 2 ?? ?? ???? ?? ?? ???? - 1 2 ?? ?? ???? ?? ?? ?? ?? -2 _(13) _ _This can be summarized as followed _ ?? =- 1 2?? ?? ?? ?? ????+ ?? 1 _(14) _ _ _ ?? 1 =- ?? ?? ?? ?? ???? 2 ?? ?? 2 - 1 2 ?? ?? ???? ?? ?? ?? ?? -2 _(15) _ _Using assumption 3 we obtain _ ?? 1 =- ?? ?? ?? ?? ???? 2 ?? ?? 2 + 1 2 ?? ?? ???? ?? ?? -2 ?? ?? =0 _(16) _ _Using assumption 5 obtained _ ?? =- 1 2?? ?? ?? ?? ????=0 _(17) _ _Finally, we can conclude that the tracking errors and its derivatives converge asymptotically to zero without any compact set ?? (??) (??)?0 as ???8 for ??=0,1,…,??-1 [1], and the system is globally stable. Since the nonlinear function?? (??), ?? (??), ??(??), and the exogenous disturbance are unknown, so the implementation of the ideal control law presented in (7) is hard.

In this situation, our goal is to approach this ideal control law using fuzzy systems. Fuzzy Logic Systems It is shown and proved that fuzzy systems are capable of approximating any real continuous function over a compact set with arbitrary precision given by [23]. Sugeno and the employee [24] have proposed a class of fuzzy systems that allows representing knowledge that is expressed in analytical form, describing the internal structure of the system.

This class of fuzzy system is called Fuzzy systems Takagi-Sugeno (TS). Note by ??= [?? 1 ,…, ?? ??] ?? is the input of fuzzy system and ?? its output . For each ?? ?? is associated ?? ?? fuzzy sets ?? ?? ?? in ?? ?? , as for ?? ?? ? ?? ?? there is at least one degree of membership ?? ?? ?? ?? (?? ??)?0 where ??=1,2,…,?? and ??=1,2,…, ?? ?? . The basic rules of the fuzzy system has ??= ??=1 ?? ?? ?? fuzzy rules of the form: _ ?? ?? :???? ?? 1 ???? ?? 1 ?? ??????…?????? ?? ?? ???? ?? ?? ?? ??h???? ??= ?? ?? ?? ,??=1,…,?? _(18) _ _Where ?? ?? ?? ? ?? ?? 1 ,…, ?? ?? ?? ?? et ?? ?? ?? is a numerical function on the output space in general, ?? ?? ?? is a polynomial function depending on variable inputs, but it can also be an arbitrary function so that it can properly describe the behavior of the studied system if ?? ?? ?? is a function: _ ?? ?? ?? = ?? 0 ?? + ??=1 ?? ?? ?? ?? ?? ?? _(19) _ _Then it's the first order Takagi-Sugeno (TS1). If against ?? ?? ?? is a polynomial of zero-order as _ ?? ?? ?? = ?? ?? _(20) _ _We have the Tackagi-Sugeno zero order (TS-0).

In this work we will consider a fuzzy zero order (TS-0). Each rule has a numerical conclusion, the total output of the fuzzy system is obtained by calculating a weighted average, and in this manner the time consumed by the procedure of defuzzification is avoided. Then the output of fuzzy system is given by following relationship [25-28]: _?? ?? = ??=1 ?? ?? ?? (??) ?? ?? (??) ??=1 ?? ?? ?? (??) _(21) _ _With ?? ?? ?? = ??=1 ?? ?? ?? ?? ?? And ?? ?? ?? ? ?? ?? 1 ,…, ?? ?? ?? ?? which represents the degree of confidence or activation rule ?? ?? .

We can simplify the output of the fuzzy system as follows: _?? ?? = ??=1 ?? ?? ?? ?? ?? ?? ??=1 ?? ?? ?? ?? _(22) _ _By introducing the concept of fuzzy basis functions [25], the output of fuzzy system TS-0 can be written as: _?? ?? = ?? ?? ?? ?? _(23) _ _Where ??= ?? 1 … ?? ?? is a vector of parameters of the conclusion of rules fuzzy part and ?? ?? = [?? 1 ?? … ?? ?? ??] ?? is the basic function of the vector each component is given by: _ ?? ?? ?? = ?? ?? (??) ??=1 ?? ?? ?? (??) ,??=1, … ,?? _(24) _ _Adaptive Fuzzy Fault-Tolerant Design This section is devoted to approach the ideal control law in order to ensure the tracking of a given reference trajectory.

To reach these objectives, a fuzzy system is used to estimate the control law as a whole (direct approach). According to the property of the universal approximation [23] of fuzzy systems, the ideal control law can be approached by a fuzzy system of the form (23) as follows _ ?? * = ?? ?? ?? ?? * +?? ?? _(25) _ _With ??(??)the approximation error,??(??) is a vector of fuzzy basis functions assumed properly set in advance by the user, and ?? * is somehow the vector of optimal parameters minimizing ??(??) .

_ ?? * =?????? ?????? ?? ?????? ?? ?? * - ?? ?? ?? ?? _(26) _ _We assume that the approximation error is bounded as follows: ??(??) = ?? ?? with ?? ?? is an unknown positive constant. Note the lower bound of the approximation error ?? ?? depends on the fuzzy basis functions selected, the more these functions are suitably chosen, the more ?? ?? is small. Since the optimal parameters ?? * are unknown, it is necessary to estimate for the synthesis of controller.

Whether ?? the estimate of ?? * and will be calculated from an adaptation algorithm, besides the fuzzy adaptive approximation of ideal law is defined by _ ?? = ?? ?? ??+ ?? ?? _(27) _ _Now we consider the following control law: _??= ?? = ?? ?? ??+ ?? ?? _(28) _ _Where ?? ?? is a robust control to get around the problem of approximation errors, it is defined by _ ?? ?? =???????? ?? ?? ???? ?? ?? - ?? 2 ?? ?? ???? _(29) _ _The adaption laws corresponding to the estimation parameters are selected as follow: _ ?? =?? ?? ?? ?????? ?? _(30) _ _ _ ?? ?? = ?? ?? ?? ?? ???? _(31) _ _ _ ?? =- ?? 0 ?? _(32) _ _when ?? is the time-varying parameter with ?? ?? >0, ??>0, ?? 0 >0 Remark 1 The overall scheme of the proposed approach is depicted in Fig. 1.

Theorem: Consider the faulty system (2c) respecting the assumptions (1-6). The control law defined by (28) and (29) with adaptions law (30-32) ensure the following properties: The tracking error and its derivatives converge to zero, ?? ?? (??)?0 when ???? for??=0,1,...??-1. The output of the system and its derivatives up to the order (??-1) and the control signal are bounded: ?? ?? , ?? ?? ,..., ?? ??-1 ?? , ??(??)?? ?? ? .

Proof _ ?? (??) = ?? ?? (??) - ?? ?? = ?? ?? ?? -?? ?? - ?? ?? ??,?? -??(??)-?? ?? ??+?? ?? ?? * -?? ?? ?? * _(33) _ _where ?? * is the ideal control law, considered as an unknown term introduced just for theoretical purpose and its value is unnecessary for the design of the proposed controller. _ ?? (??) = ?? ?? ?? -?? ?? - ?? ?? ??,?? -??(??)+?? ?? ?? * -?? -?? ?? ?? * _(34) _ _Replacing equation (7), (34) becomes _ ?? (??) =- ?? ?? ??+?? ?? ?? * -?? -?? ?? ?? ?? 2 ?? ?? 2 ?? ?? ???? ?? ?? ???? _(35) _ _Let write the ideal control law as follows _ ?? * = ?? ?? ?? * + ?? ?? ?? _(36) _ _Let consider the adaptive control term as follows _??= ?? = ?? ?? ??+ ?? ?? _(37) _ _Then, combining equation (36) and (37), one can find _ ?? * -??= ?? ?? ?? + ?? ?? ?? -?? ?? _(38) _ _Where _ ?? = ?? * - ?? _(39) _ _ _ ?? (??) =- ?? ?? ??+?? ?? ?? ?? ?? + ?? ?? ?? - ?? ?? -?? ?? ?? ?? 2 ?? ?? 2 ?? ?? ???? ?? ?? ???? _(40) _ _Then the error dynamics can be written as follows: _ ?? =????+?? ?? ?? ?? ?? ?? + ?? ?? ?? - ?? ?? -??(??) ?? ?? 2 ?? ?? 2 ?? ?? ???? ?? ?? ???? _(41) _ _where ??= 0 1 ? 0 ? ? ? 0 0 - ?? ?? 0 - ?? ??-1 ? 1 ... - ?? ?? ??= 0 ? 0 1 Until (????-??)= ?? (??) + ?? 1 ?? (??-1) +...+ ?? ?? is stable (A stable), we know that there exists a symmetric positive definite matrix ?? (??, ??) that satisfies the Lyapunov equation: _ ?? ?? ??+????=-?? _(42) _ _Where ??(?? ?? ??) is a symmetric positive definite matrix.

Whether ?? is the Lyapunov-like equation function, then _??= 1 2??(??) ?? ?? ????+ 1 2?? ?? ?? ?? + 1 2 ?? ?? ?? ?? 2 + 1 2 ?? 0 ?? 2 _(43) _ _ _ ?? =- 1 2?? ?? ?? ?? ????+ ?? ?? ????

?? ?? -1 ?? ?? ?? ?? ?? + ?? ?? ?? - ?? ?? -?? ?? ?? ?? 2 ?? ?? 2 ?? ?? ???? ?? ?? ???? - 1 2 ?? ?? ???? ?? ?? 2 ?? ?? - 1 ?? ?? ?? ?? - 1 ?? ?? ?? ?? ?? ?? + 1 ?? 0 ?? ?? _(44) _ _ _ ?? =- 1 2?? ?? ?? ?? ????- 1 2 ?? ?? ???? ?? ?? 2 ?? ?? + ?? 1+ ?? 2 _(45) _ _With _ ?? 1= ?? ?? ???? ?? ?? ?? - 1 ?? ?? ?? ?? _(46) _ _Then _ ?? 2= ?? ?? ???? ?? ?? ?? - ?? ?? ?????? ?? - ?? ?? ?? ?? ???? 2 ?? ?? 2 - 1 ?? ?? ?? ?? ?? ?? + 1 ?? 0 ?? ?? _(47) _ _Using equation (30) _ ?? 1=0 _(48) _ _Using assumption 6 _ ?? 2= ?? ?? ???? ?? ?? - ?? ?? ?????? ?? - ?? ?? ?? ?? ???? 2 ?? ?? 2 - 1 ?? ?? ?? ?? ?? ?? + 1 ?? 0 ?? ?? _(49) _ _Using (29), (31) and (32) _ ?? 2=- ?? ?? ?? ?? ???? 2 ?? ?? 2 _(50) _ _The whole Lyapunov-like equation can be described as _ ?? =- 1 2?? ?? ?? ?? ????- 1 2 ?? ?? ???? ?? ?? 2 ?? ?? - ?? ?? ?? ?? ???? 2 ?? ?? 2 _(51) _ _Using assumption 3 _ ?? =- 1 2?? ?? ?? ?? ????=- 1 2 ?? ?? ?? ????=0 _(52) _ _Hence ???? ?? 8 which implies that the signals ?? ?? , ?? ?? , ?? ?? and ??(??) is bounded.

This implies the boundedness of ?? ?? , ?? ?? , and ?? (??), by using Babalat's lemma, we conclude that the tracking errors and its derivatives converge asymptotically to zero ?? (??) (??)?0 when ???8 for ??=0,1,...,??-1. / Fig. 1. The overall scheme Results and Discussion In this section, an inverted pendulum model is chosen to test the accuracy and the prompt of the proposed method, so let consider the tracking control of the following inverted pendulum system depicted in Fig. 2. The dynamic equations of such a system are given as in [25].

_ ?? 1 = ?? 2 ?? 2 =?? ?? +?? ?? ??+??(??) ??= ?? 1 _(53) _ _With _?? ?? = ???????? ?? 1 - (???? ?? 2 2 ?????? ?? 1 ?????? ?? 1) ?? ?? + ?? ?? ?? 4 3 - ?? ?? ?????? 2 ?? 1 ?? ?? + ?? ?? _(54) _ _ _?? ?? = ?????? ?? 1 ?? ?? + ?? ?? ?? 4 3 - ?? ?? ?????? 2 ?? 1 ?? ?? + ?? ?? _(55) _ _Where ?? 1 is the rotation movement, ?? 2 is the rotation velocity, ??=9.8??/ ?? 2 is the acceleration due to gravity, ?? ?? is the mass of the cart, ?? ?? is the mass of the pole, ?? is the half-length of the pole, and ?? is the applied force values. The variable ?? ?? =1???? , ?? ?? =0.1???? and ??=0.5?? are chosen in this example.

The control objective is to force the output system to follow the desired trajectory ?? ?? ?? = sin ?? . Note that the desired trajectory allowed a maximum swing of 1 ??????, while it is limited to 0.1 rad in [25], the exogenous disturbance is given as ?? ?? =0.45sin?(3??). / Fig. 2. The used inverted pendulum Only one fuzzy system taking the form of (23) is used to approximate the ideal control law. The fuzzy system inputs are selected as ?? 1 (??) and ?? 2 (??). Each input has five Gaussian membership functions defined as ?? ?? ?? 1 (?? ??)=exp? - 1 2 ?? ?? +1.8 0.22 2 ?? ?? ?? 2 (?? ??)=exp? - 1 2 ?? ?? +1.4 0.22 2 ?? ?? ?? 3 (?? ??)=exp? - 1 2 ?? ?? 0.22 2 ?? ?? ?? 4 (?? ??)=exp? - 1 2 ?? ?? -1.4 0.22 2 ?? ?? ?? 5 (?? ??)=exp? - 1 2 ?? ?? -1.8 0.22 2 The initial value of the parameter ?? ?? is randomly chosen.

The various parameters used in this simulation are chosen as follows: ??= 1,2 , ??= 15 5;5

5 , ??= 0;1 ??=100 , ?? 0 =10, ?? ?? =0.001 The initial value of ??(0) is chosen randomly between (-2 and 2) and ?? ?? 0 =0, ?? 0 =3. We curried out this simulation with actuator faults instead of sensor faults. The faults time profile is chosen to be at the start of the simulation time, and the form of actuators faults is considered with the followings parameters: 1) Bias 0.005 ??.?? ; 2) Drift with coefficient ??=0.07; 3) Loss of accuracy defined by a square waveform having an amplitude equal to (0.0087 ??.??) with the frequency of 0.15 ????; 4) Loss of effectiveness with 75%.

The simulation results of the angular position ??= ?? 1 and the angular velocity ?? = ?? 2 are shown in Fig. 3 and Fig. 4, respectively. The control input signal ??(??) is shown in Fig. 5. The tracking error signal ??(??) is depicted in Fig. 6. We can figure out that the system output converges to the desired trajectory in a short time, even in the presence of actuator faults. So, one can conclude the tracking capability and the precise result of the proposed control strategy. / Fig. 3. ?? ?? angular position signal (solid lines) and ?? ?? (??) reference signal (dashed lines) / Fig. 4. ?? ?? angular velocity signal (solid lines) and ?? ?? (??) reference signal (dashed lines) / Fig. 5. Applied control input signal / Fig. 6.

Tracking error signal ?? ?? ?? -?? ?? Based on the aforesaid result (Fig. 2-6), we can figure out the proposed approach reaches a good tracking performance against uncertainties, exogenous disturbances, and actuator faults. The position of the inverted pendulum ??(??) reaches the desired trajectory ?? ?? (??) in few seconds (around 2.5 seconds) as shown in Fig. 3 even in the presence of actuator faults, with acceptable angular velocity as depicted in Fig. 4, and the applied effort is smooth without any chattering phenomenon and acceptable power (no saturation) as shown in Fig. 5. Finally, the tracking error is closer to the origin (see Fig. 6), which implies that the control objective is reached.

Conclusion In this work, direct adaptive fuzzy fault-tolerant control for a class of unknown nonlinear systems subjected to time-varying actuator faults and exogenous disturbance is investigated. Fuzzy logic systems FLSs are employed to estimating the whole adaptive control law along with the actuator and the exogenous disturbance and one robust controller term to compensate the approximation errors due to the use of the FLSs. The controller does not need the mathematical model of the plant, and no-fault detection and isolation FDI units are needed.

The boundedness of all signals involved in the closed-loop system and the convergence of the tracking error to zero are ensured based on the Lyapunov-like equation and Barbalat’s lemma. The novelty of this paper resides in the integration of actuator faults and exogenous disturbance in the approximation of the whole adaptive controller. Furthermore, the considered control gain is taken as a nonlinear function that extended the range of the studied systems.

Moreover, our approach relaxes the a priori knowledge of the lower bound of the control gain and the upper bounds of the approximation errors. In the simulation part, one example applied on an inverted pendulum shows the tracking performances of the proposed method.

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