SENSOR AND ACTUATOR FAULT-HIDING RECONFIGURABLE CONTROL DESIGN FOR A FOUR-TANK SYSTEM BENCHMARK

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Abstract. *Fault detection and compensation plays a key role to fulfil high demands for performance and security in today's technological systems. In this paper, a fault-hiding (i.e., tolerant) control scheme that detects and compensates for actuator and sensor faults in a four-tank system benchmark is introduced. Faults are modelled as a drastic gain loss in actuators (i.e., pumps) and in sensor measurements (i.e., level detection) which could lead to a large loss in the nominal performance. A configurable decentralized Proportional Integral (PI) controller is designed and applied to a Linear Time Invariant (LTI) system where virtual sensors and virtual actuators are used to correct faulty performance through the use of a pre-fault performance. Simulation results showed that the developed approach can handle different types of faults and be able to completely and instantly recover the original system performance/functionality directly after the occurrence of faults.*
Keywords: Virtual sensor, Virtual actuator, Fault Detection and Isolation (FDI), Fault-hiding control reconfiguration, Luenberger observer

1. **Introduction.** Automated systems are vulnerable to faults. Defects in sensors, actuators, in the process itself, or within the controller, can be amplified by the closed-loop control systems, and faults can develop into malfunction of the loop. The closed-loop control action may hide a fault from being observed. A situation is reached in which a fault eventually develops into a state where loop-failure is inevitable. A control-loop failure will easily cause production to stop or system malfunction at a plant level [1]. With economic demand for high plant availability, and an increasing awareness about the risks associated with system malfunction, dependability is becoming an essential concern in industrial automation. A cost effective way to obtain increased dependability in automated systems is to introduce Fault-Tolerant Control (FTC) [1]. FTC aims at making technological systems tolerant to faults. This means that the system should be able to fulfill its function also after the appearance of degradation or failure in its components due to losing one or more of the systems' actuators/sensors [2].

Reconfigurable control systems are control systems that are characterized by the ability to perform in the presence of drastic changes in the system dynamics due, for example, to abrupt system component (actuator/sensor) failures or rapid changes in the operating

conditions [3]. The objectives of these systems are; first they need to guarantee safe performance (stability), when possible, and then recover maximum control performance under impairments. Established techniques exist for the case of anticipated failures/operating conditions changes, for which control laws are pre-computed, stored and used upon need. However, the interest here is mainly for the cases of unanticipated scenarios, where an automated on-line failure accommodation technique is needed [3]. Here, we are primarily interested in the reconfiguration part. In case of component failures, a Failure Detection and Identification (FDI) scheme is assumed to provide the dynamics in terms of the state space model of the impaired system. In case of operating condition changes, an on-line modeling technique is required to identify the state-space model that corresponds to the new operating conditions. Once the model of the new/impaired system is available, a reconfigurable technique is presented to maintain its stability and performance.

Several approaches for fault-tolerant control and various applications have been developed in the last decade. See for examples, adaptive fuzzy backstepping control approaches for multiple-input multiple-output (MIMO) nonlinear systems with immeasurable states [4], a Luenberger obsever FTC based approach for nonlinear systems which are connected in a networked control system [5], and a multi-constrained full-order fault estimation observer (FFEO) with finite frequency specifications for continuous-time systems to detect and isolate disturbance and faults occurring in low-, middle-, high-frequency domains [6]. However, fault tolerant methods have been applied to multi-tank system benchmarks which have been shown in a few recent research works. Some examples are mentioned in the following. Dardinier-Maron *et al.* proposed a feedback linearization approach for fault tolerant control in a three-tank benchmark [7]. Noura *et al.* proposed an approach based on the on-line estimation of the fault and the computation of an additive control law is able to compensate for the fault effect on the system [8]. Mendoca *et al.* have used predictive control and fuzzy logic to design a fault tolerant control for a three-tank benchmark [9]. Orani *et al.* presented a global observer based on a second-order sliding mode control algorithm for the simultaneous fault detection, isolation, and reconstruction for a hydraulic vertical three tank system [10]. Casavola *et al.* implemented a real-time fault-tolerant approach based on a Command Governor (CG) strategy for the supervision of a laboratory four-tank test-bed [11]. Hjiani and Poshtan proposed a state feedback reconfigurable controller design based on parametric eigenstructure assignment (PEA) technique that has the capacity to be reconfigured in the case that partial actuator faults occur [12].

In this paper, a reconfigurable control strategy for continuous Linear Time Invariant (LTI) systems is presented. Reconfigurable control is an important technology for building truly autonomous dependable systems. Reconfigurable control is designed to respond to component faults that would otherwise break the control loop [13]. Figure 1 shows the role of control reconfiguration in an active fault-tolerant control context. The reconfiguration component obtains an estimate $\hat{f}$ of the fault f from a diagnosis component (FDI) and changes the controller to match the faulty plant once the fault has been isolated. Numerous reconfigurable control methods for linear systems have been developed.

The method presented here is based on the idea of keeping the nominal controller in the loop by inserting a reconfiguration block between the faulty plant and the nominal controller after a fault has occurred. The reconfiguration block is chosen to "hide" the fault from the controller and at the same time to ensure that the faulty plant controlled by the nominal controller together with the reconfiguration block remains globally input-to-state stable with respect to reference inputs. We applied this method to the Quadruple-Tank Process (QTP) control. The rest of the paper is organized as follows. QTP control is presented in Section 2. Section 3 introduces the proposed fault hiding approaches.
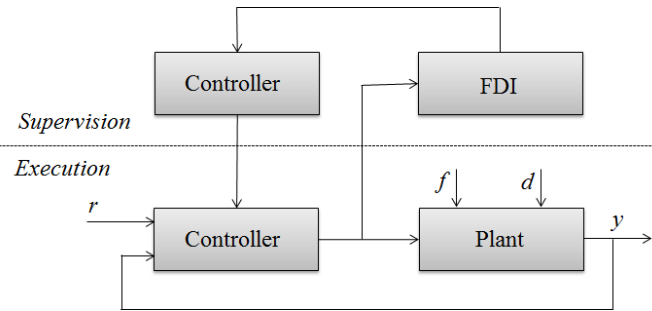
FIGURE 1. Active Fault-Tolerant Control (FTC)

Experimental results of applying the proposed approach to the four tank benchmark system is presented in Section 4. Finally, concluding remarks are presented in Section 5.

2. Quadruple Tank Process Control.

2.1. **Model description.** QTP control is a combination of two double tank systems, schematically shown in Figure 2. In this section, the nonlinear model of a quadruple-tank process derived in [14] is used to test and validate the proposed methodology. The process consists of four interconnected water tanks and two pumps. Its inputs are the voltages to the two pumps and the outputs are the water levels in the lower two tanks. The linearized model of the quadruple-tank process has a multivariable zero, which can be located in either the left or the right half-plane by simply changing a valve. It is shown that the valve positions of the process uniquely determine if the system is minimum phase
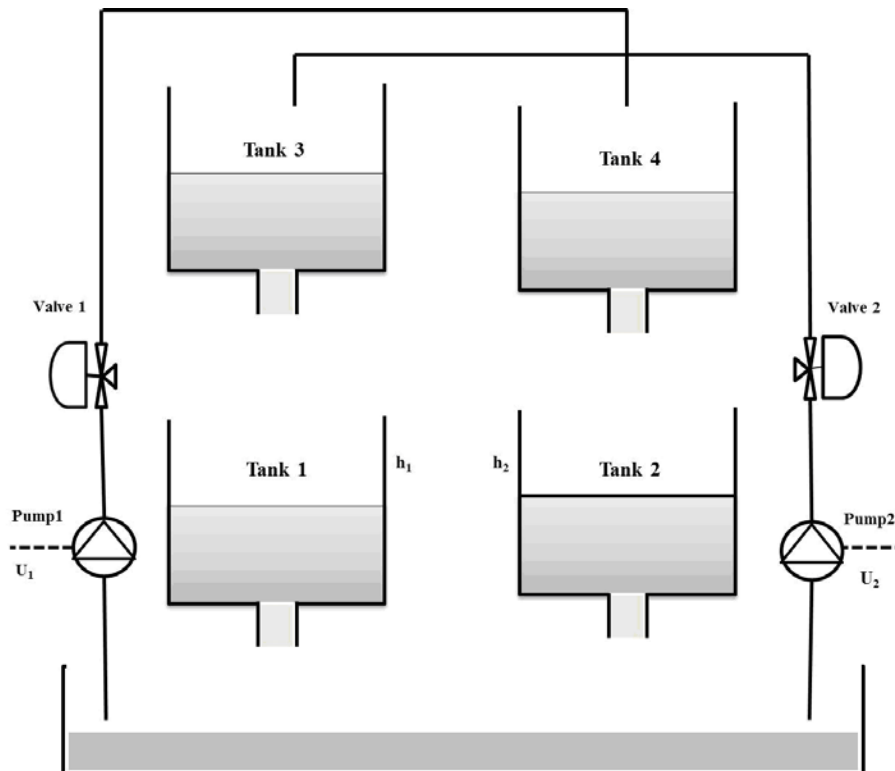

FIGURE 2. Schematic diagram of the (QTP) [14]

or non-minimum phase [15]. The nonlinear model equations are given as follows:

$$\frac{dh_1}{dt} = -\frac{a_1}{A_1}\sqrt{2gh_1} - \frac{a_3}{A_3}\sqrt{2gh_3} + \frac{\gamma_1 k_1}{A_1}u_1$$

$$\frac{dh_2}{dt} = -\frac{a_2}{A_2}\sqrt{2gh_1} - \frac{a_4}{A_4}\sqrt{2gh_4} + \frac{\gamma_2 k_2}{A_2}u_2$$

$$\frac{dh_3}{dt} = -\frac{a_3}{A_3}\sqrt{2gh_3} + \frac{(1-\gamma_2)k_2}{A_3}u_2$$

$$\frac{dh_4}{dt} = -\frac{a_4}{A_4}\sqrt{2gh_4} + \frac{(1-\gamma_1)k_2}{A_4}u_1$$

$$(1)$$

where A_i is the cross-sectional area of tank i, a_i is the cross-sectional area of the outlet hole i, h_i is the water level in tank i, and g is the acceleration due to gravity (i.e., 9.81 m/s^2). The voltage applied to pump i is u_i and the corresponding flow is $k_i u_i$. The parameters γ_1, $\gamma_2 \in [0,1]$ are determined from how the valves are set prior to an experiment. The flow to Tank 1 is $\gamma_1 k_1 u_1$ and the flow to Tank 4 is $(1-\gamma_1)k_1 u_1$ and similarly for Tank 2 and Tank 3. The measured level signals are $k_c h_1$ and $k_c h_2$ [14]. Process parameters are given as A_1, $A_3 = 28$ cm^2, A_2, $A_4 = 32$ cm^2, a_1, $a_3 = 0.071$ cm^2, a_2, $a_4 = 0.057$ cm^2, $k_c = 0.5$ V/cm, $g = 981$ cm/s^2.

The linearized state-space equation is given by

$$\frac{dx}{dt} = \begin{bmatrix} -\frac{1}{T_1} & 0 & \frac{A_3}{A_1 T_1} & 0 \\ 0 & -\frac{1}{T_2} & 0 & \frac{A_4}{A_2 T_4} \\ 0 & 0 & -\frac{1}{T_3} & 0 \\ 0 & 0 & 0 & -\frac{1}{T_4} \end{bmatrix} x + \begin{bmatrix} \frac{\gamma_1 K_1}{A_1} & 0 \\ 0 & \frac{\gamma_2 K_2}{A_2} \\ 0 & \frac{(1-\gamma_2)K_2}{A_3} \\ \frac{(1-\gamma_1)K_1}{A_4} & 0 \end{bmatrix} u \qquad (2a)$$

The output equation is designed as it is discussed above is given by:

$$y = \begin{bmatrix} K_c & 0 & 0 & 0 \\ 0 & K_c & 0 & 0 \end{bmatrix} x \qquad (2b)$$

where the time constants are given by:

$$T_i = -\frac{A_i}{a_i}\sqrt{\frac{2h_i^o}{g}}, \quad \forall i = 1,\dots,4 \qquad (3)$$

The operating point parameter values of the process are h_1, h_2, h_3, $h_4 = 12.4$, 12.7, 1.8, 1.4 cm respectively, u_1, $u_2 = 3$, 3 v, k_1, $k_2 = 3.33$, 3.35 cm^3/vs, and γ_1, $\gamma_2 = 0.6$, 0.7. As it is mentioned above, the linearized dynamics of the process exhibits a multivariable zero that can be moved from one side of the complex plane to the other one by changing the valves positions. Furthermore, the system is minimum phase when $1 \le \gamma_1 + \gamma_2 \le 2$ and is in non-minimum phase when $\gamma_1 + \gamma_2 \le 1$. This process is found to be ideally suited to illustrate many concepts in multivariable control.

2.2. **Decentralized Proportional-Integral (PI) controller design.** The decentralized control law will be in the form $u = \text{diag}\{C_1, C_2\}.$ $(r-y)$, where r is the desired set point as it is shown in Figure 3 [16].

In this paper, a proportional integral (PI) controller of the form

$$C_l = K_{Pl} + \frac{K_{Il}}{s}, \quad \forall l = 1, 2 \qquad (4)$$

is used, the controller is tuned using the formula [17].

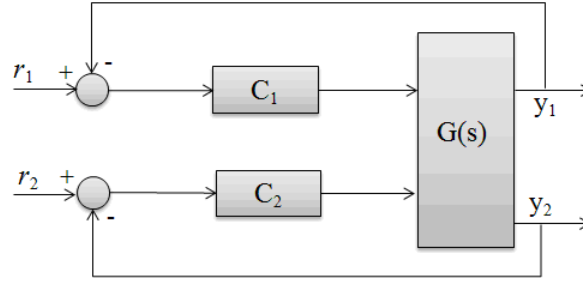$$K_{Il} = \frac{T_{Il}}{K_P T_c}, \quad T_c = 0.5\, T_{il}, \quad l = 1, 2 \qquad (5)$$

FIGURE 3. Decentralized PI structure; C_1 and C_2 are the two controllers of Tanks 1 and 2 respectively

An interactive Matlab® GUI tool called sisotool, which is used for the analysis, design and verification of control systems, is used here to select and tune the controller parameters based on Ziegler-Nichols approach.

3. Fault-Hiding Approach.

3.1. **General.** The fault hiding reconfigurable control approach is based on the idea of placing a reconfiguration block $\sum_R$ between the nominal controller $\sum_C$ and the faulty plant $\sum_{FP}$ at reconfiguration time, as it is shown in Figure 4. The reconfiguration block hides the fault from the controller and helps the faulty plant to operate ideally. In other words, the reconfigured plant $\sum_{RP}$ seen from the signal pair (u_c, y_c) must have the same input/output behavior as the nominal plant $\sum_P$ seen from the signal pair (u_c, y_f). The reconfiguration block contains a virtual sensor (an observer-like system) and a virtual actuator (a dual observer-like system) in the general case. Apart from fault-hiding, the reconfiguration block must achieve as many of the following goals as possible. The reconfigured closed-loop system $(\sum_{FP}, \sum_R, \sum_C)$ must be stable, should be able to recover the tracking properties of the nominal closed-loop system $(\sum_P, \sum_C)$, and should be able to recover the performance properties of the nominal closed-loop system.

3.2. **The virtual sensor.** Since this reconfiguration problem is very similar to an observation problem, the derivation of the virtual sensor is similar to the design of a state observer. The derivation can be found in advanced text books, e.g., [15] or [18], and is
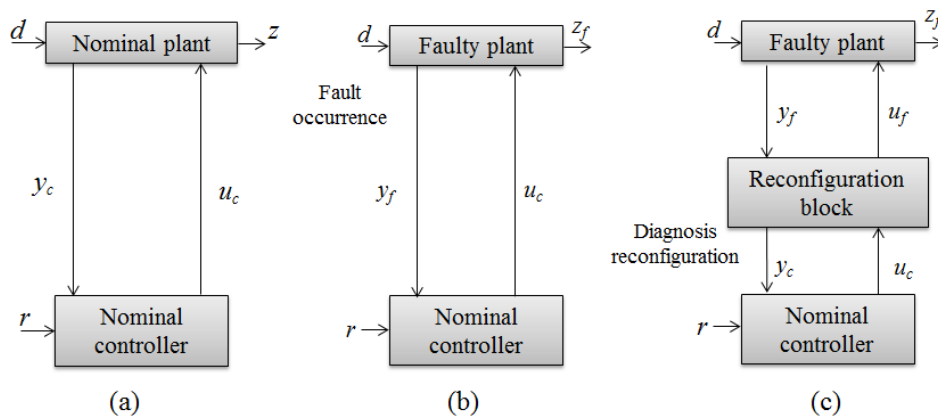

FIGURE 4. (a) Nominal closed loop system, (b) faulty closed loop system prior to diagnosis and reconfiguration, (c) reconfigured closed loop system
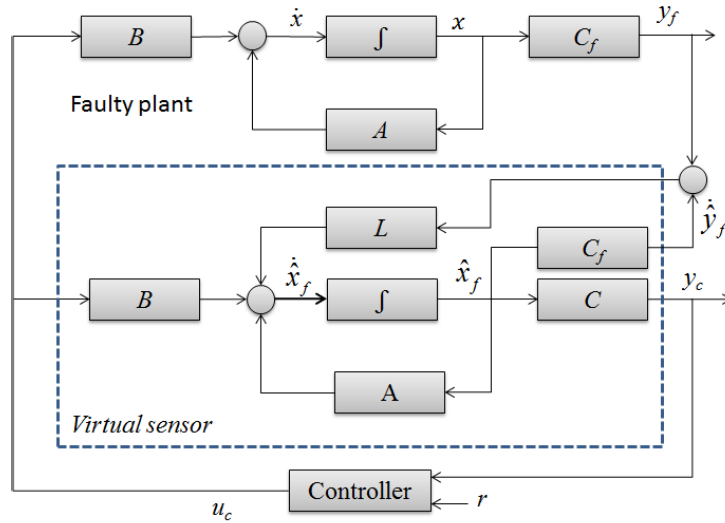
FIGURE 5. Closed-loop system reconfiguration after occurance of sensor fault by means of a virtual sensor which is adapted to the fault

given by:

$$\dot{\widehat{x}} = A\widehat{x} + Bu_c + L\left(y_f - C_f\widehat{x}\right) \tag{6}$$

while the rest of the system remains unchanged, as it is shown in Figure 5. The parameter L^T is chosen to stabilize the pair: $\left(A^T, C_f^T\right)$ that all poles are within the design set C_g that is:

$$\sigma\left(A - LC_f\right) \subseteq C_g \tag{7}$$

The resulting block is called a virtual sensor, and it solves the reconfiguration problem with respect to the stabilizing goal and the fault-hiding goal. The virtual sensor consists of a Luenberger observer, the output matrix C and the necessary input signal connections.

3.3. **The virtual actuator.** The idea of a virtual actuator is to use the input signal meant for the nominal process and to transform it into a signal useful for the remaining actuators of the faulty plant Figure 6. The nominal plant is given in the state space form:

$$\begin{aligned} \dot{X} &= AX + Bu, \\ y &= CX. \end{aligned} \tag{8}$$

And the faulty plant is given by;

$$\begin{aligned} \dot{X}_f &= AX_f + B_f u_f, \\ y_f &= CX_f. \end{aligned} \tag{9}$$

The two models differ only when $B \neq B_f$.

The stabilization goal is obviously not reachable, if the faulty plant contains fixed poles outside of C_g. Since the controllability of the plant has not changed due to the fault, only unobservable poles outside of C_g are relevant here. Consequently, a necessary condition for the problem to be solvable is that all unobservable poles of the faulty plant are within C_g.

The parameter M is chosen to stabilize the pair: (A, B_f) that all poles are within the designated set C_g where:
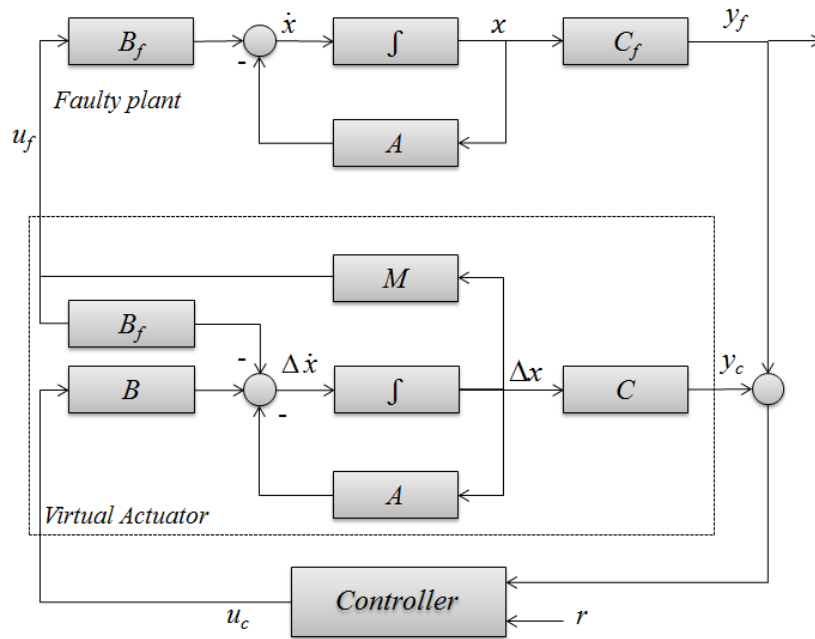
$$\sigma\left(A - B_f M\right) \subseteq C_g \tag{10}$$

FIGURE 6. Closed-loop system reconfiguration after occurance of actuator fault by means of a virtual actuator which is adapted to the fault

The virtual actuator as defined by the state-space model can be described as:

$$\dot{X}_\Delta = (A - B_f M) X_\Delta + B u_c,$$
$$y_c = y_f + C X_\Delta, \qquad\qquad\qquad (11)$$
$$y_f = M X_\Delta,$$

where $X_\Delta(0) = 0$.

When a fault occurs in both a sensor and/or an actuator at the same time ($B_f \neq B, C_f \neq C$) which is very rare case, the reconfiguration block is realized by the inter connection of the following virtual sensor and virtual actuator ($\sum_S, \sum_A$) paradigm shown in Figure 7. The virtual sensor is essentially an observer for state of the faulty plant. It consists of a model of the faulty plant augmented by output error injection. The virtual actuator contains a reference model for the nominal plant along with feedback of the difference between the reference state and the observed state, as well as feed through of the control input, as it is shown in Figure 7.

4. **Experimental Results.** The proposed algorithm is implemented using Matlab® running on an Intel(R) Core(TM) i5 CPU platform with 2GB RAM running Windows™ 7. Several simulation experiments have been conducted to evaluate and validate the functionality of the proposed technique in recovering system performance in cases of fault occurrence in sensors and in actuators. In Section 4.1, fault-free system and controller response for change in set-points is presented. The capability of the proposed fault-hiding approach to recover adequate system performance due to sensory and actuator faults are presented in Sections 4.2 and 4.3, respectively.

4.1. **Fault-free system and controller response.** In this section, fault free system and controller response for step changes in water level in Tanks 1 and 2 are presented. In this experiment, the water level in Tank 1 is raised from 25 cm to 30 cm at $t = 150$ s while the water level in Tank 2 is raised from 20 cm to 35 cm at $t = 400$ s, as it is shown in Figure 8 (upper). Figure 8 (bottom) shows the control commands which help the system
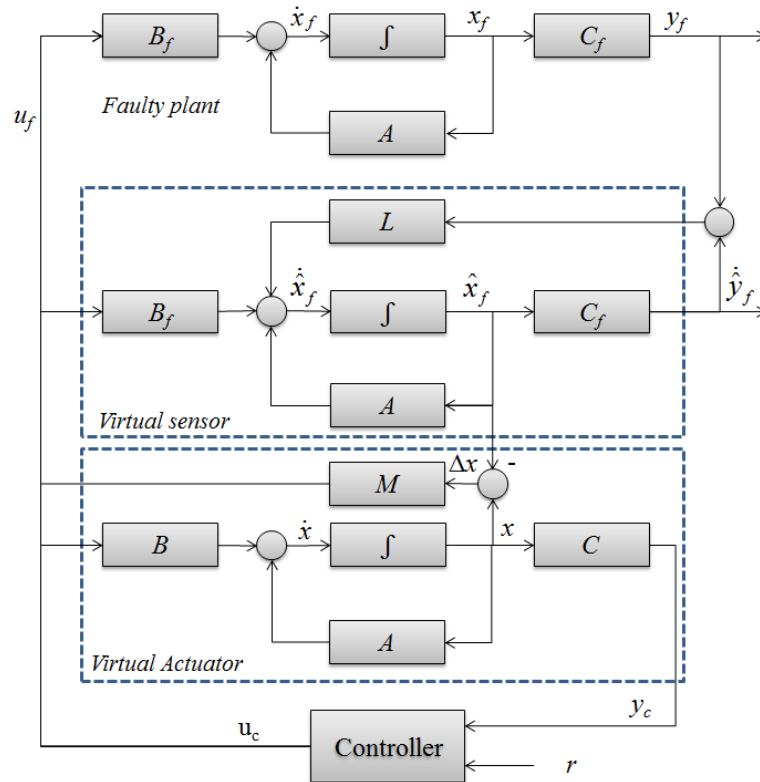
FIGURE 7. Reconfigured closed-loop system after occurance of sensor and actuator faults by means of a virtual sensor and a virtual actuator which are adapted to the faults

to accurately track the desired set values. It is obvious that the system performance and the controller response are adequate and the two tanks are almost fully decoupled and behave independently of each other.

4.2. **Fault detection in Sensor 1.** In this section, the capability and performance of the fault-hiding reconfiguration approach in keeping the water level in Tanks 1 and 2 at the desired set-values regardless of the fault occurrence in sensors is presented. Here, a partial fault is introduced in Sensor 1 which measures the level in Tank 1 with a sensor effectiveness factor, α, of 0.5 at $t = 300$ s. In Figure 9, the waters levels in Tanks 1 and 2 and the its relevant control signals in case of undetected faults are shown in dotted lines while the corrected water levels and corrected control signals in case of detecting and isolating faults are shown in solid lines. Before fault occurrence, the sensor reading of the water level in Tank 1 was 30 cm and after fault occurrence it abruptly decreases to 15 cm (i.e., 50% reduction in sensor reading than actual and true value due to sensor fault), as it is shown in dotted line in Figure 9 (upper-left). By applying the fault tolerant control (i.e., fault-hiding) reconfigurable control algorithm on the faulty system, the controller instantly detected the fault and behaved normally, as it is shown in solid line in Figure 9 (upper-left). The control signal, U1, in case of faulty system is shown in dotted line in Figure 9 (bottom-left) while the reconfigurable control command is shown in solid line where the fault was successfully identified and considered and therefore the system response becomes normal even in the presence of such kind of sever fault. The water level in Tank 2 is shown in Figure 9 (upper-right) and the relevant control commands in both cases are shown Figure 9 (bottom-right).
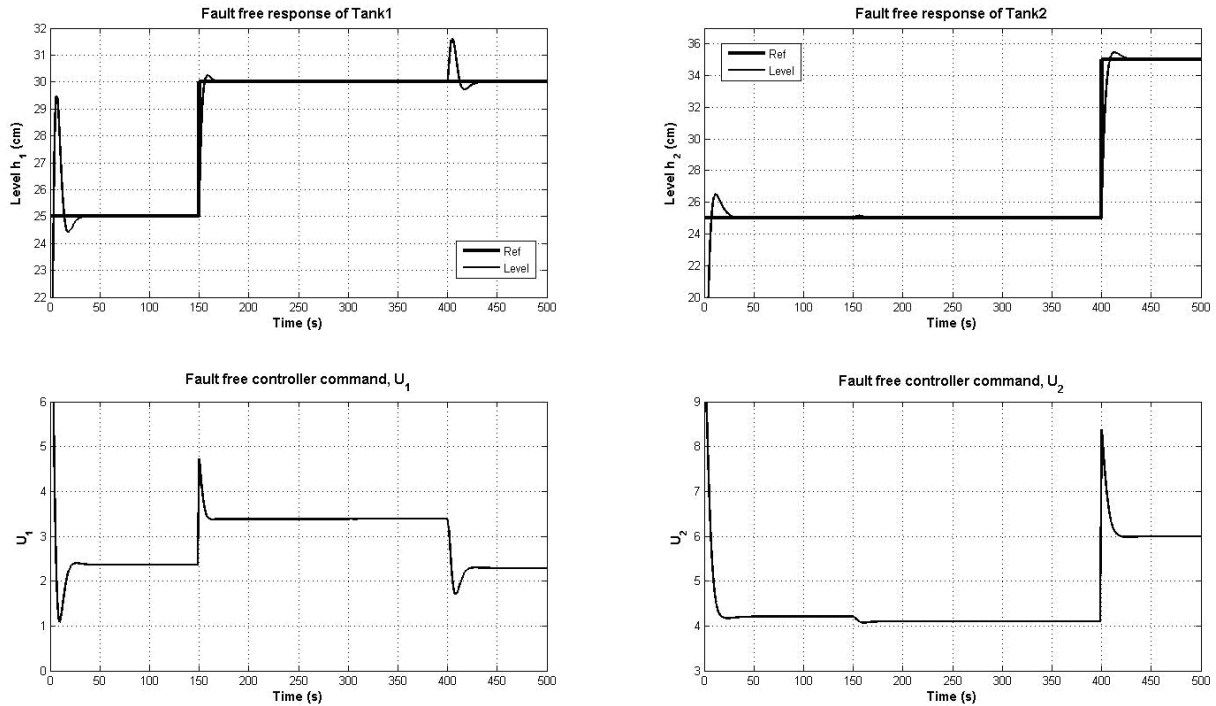
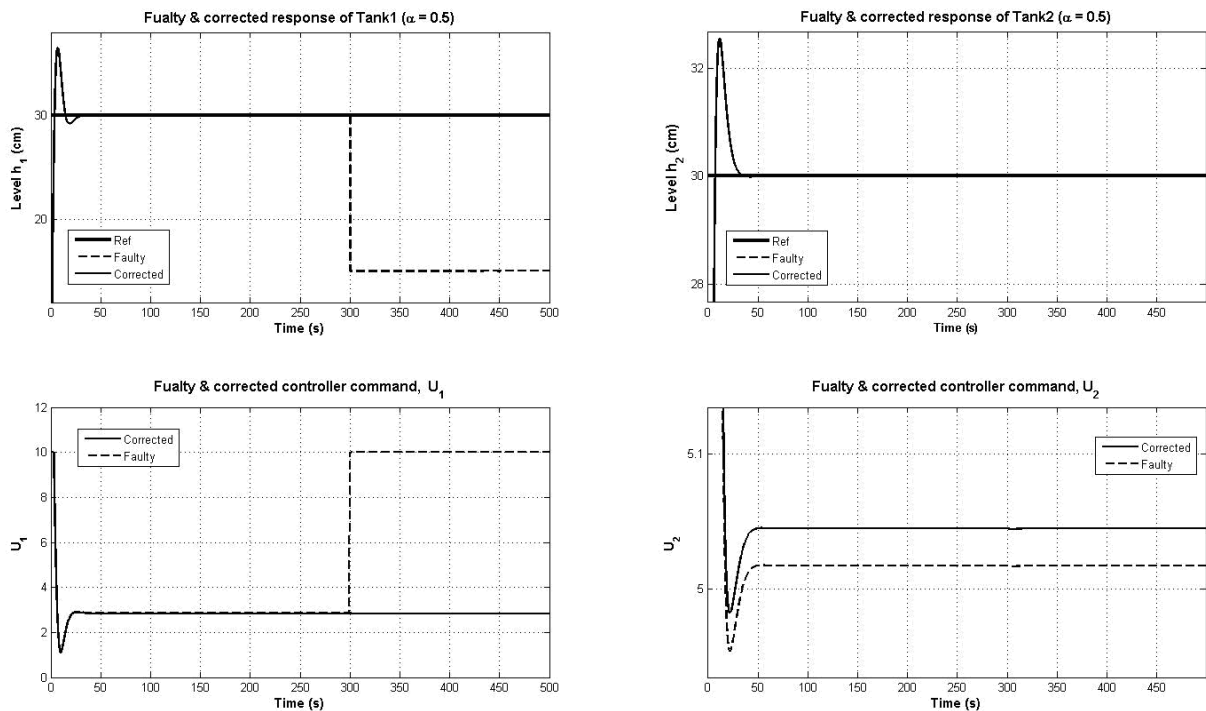FIGURE 8. Free system response and controllers' commands

FIGURE 9. Corrected and faulty system response and controllers' commands (a fault in the first sensor)

4.3. **Fault detection in Actuator 1.** In this section, a partial fault with an effectiveness factor, α, of 0.77 is introduced in the actuator of Tank 1 (i.e., valve 1) at $t = 300$ s. Upon occurrence of the actuator's fault, the water level in Tank 1 is highly affected compared to the water level in Tank 2 and this is because the water level in Tank 1 is directly affected by the control signal U1 while the water level in other tanks are less affected
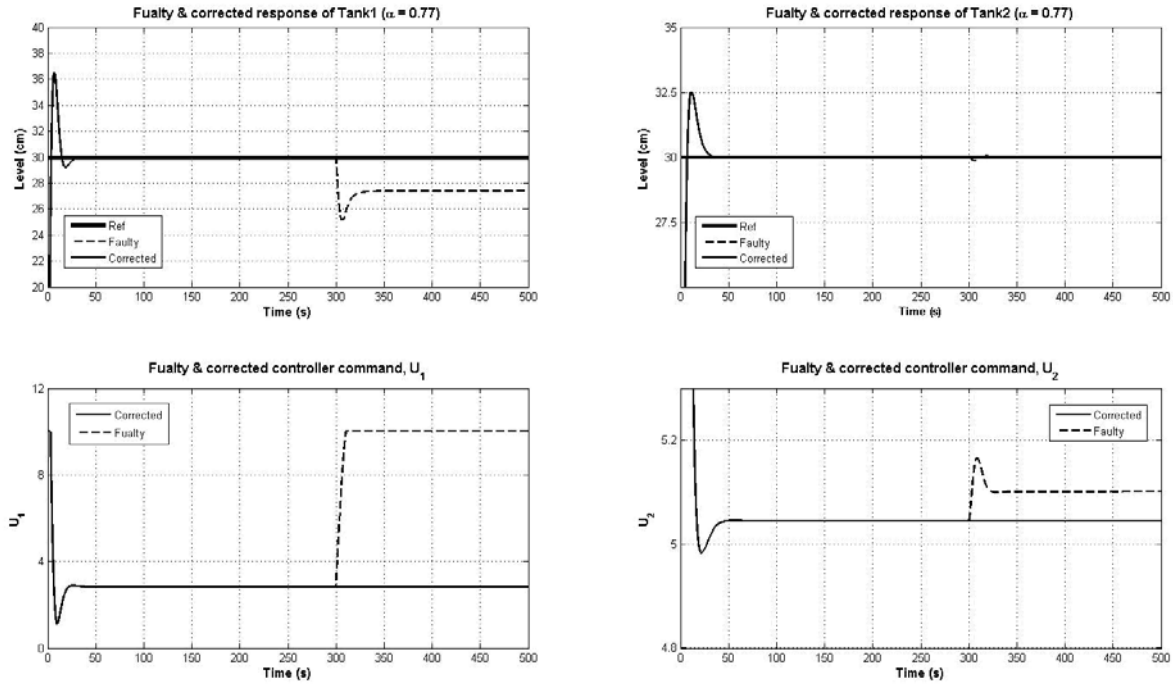
FIGURE 10. Corrected and faulty system response and controllers' commands (a fault in the first actuator)

by this change, as it is obvious by Equation (1). Once the fault occurs, the controller commands are highly affected and this could lead to disastrous scenarios if the fault cannot be detected and dealt with instantly and therefore the need arises to detect such kind of faults and isolate it and treat it in a manner to minimize its risk and achieve adequate system response and safety. In Figure 10, the water levels in Tanks 1 and 2 and its relevant control signals in case of undetected faults are shown in dotted lines while the corrected water levels and the corrected reconfigurable control signals in case of detecting and isolating faults are shown in solid lines. By applying the fault tolerant reconfigurable control (i.e., fault hiding) approach on the faulty system, the system can instantly detect and isolate faults and let the controller work normally to achieve the system's desired response even in the presence of such kinds of sever faults.

4.4. **Fault detection in both Sensor 1 and Actuator 1.** In this section, at $t = 300$ s, a partial fault with a sensor effectiveness factor, α_{sensor}, of 0.5 is introduced in Sensor 1 which measures the water level in Tank 1 and a partial fault with an effectiveness factor, $\alpha_{\mathrm{actuator}}$, of 0.77 is introduced in the actuator which controls the water flow to Tank 1. In Figure 11, the water levels in Tanks 1 and 2 and its control signals in case of undetected faults are shown in dotted lines while the corrected water levels and the corrected reconfigurable control signals in case of detecting and isolating faults are shown in solid lines. The developed approach helped the system to instantly retain its normal performance directly after the occurrence of faults.

5. **Conclusions.** In this paper, a novel approach for a fault-hiding reconfigurable control is presented. A configurable decentralized PI controller is designed and applied to a Linear Time Invariant (LTI) system where virtual sensors and virtual actuators are used to correct faulty performance through the use of a pre-fault performance. The fault hiding approach is designed to detect and compensate for actuator and sensor faults in a four-tank system benchmark. Simulation results showed that the proposed approach
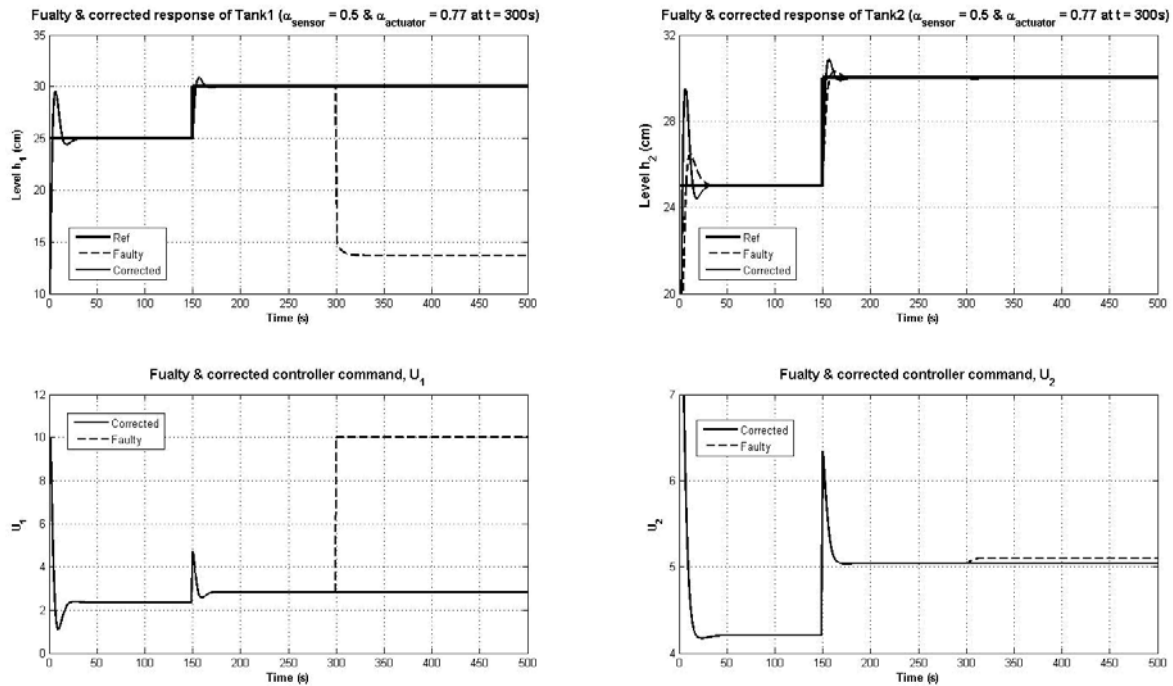
FIGURE 11. Corrected and faulty system response and controllers' commands (a fault in the first sensor and a fault in the first actuator)

can handle different types of faults and have the ability to instantly recover the original system performance/functionality completely after the occurrence of sever faults.

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