View metadata, citation and similar papers at core.ac.uk

brought to you by CORE

provided by Repository of the Academy's Library

Development of an Approach to a Biologically Inspired Self-Organizing Control Structure

Loránd Székely, Éva-H. Dulf
Department of Automation
Technical University of Cluj-Napoca
Cluj-Napoca, Romania
loriszekely@yahoo.com, eva.dulf@aut.utcluj.ro

Levente Kovács
Biomatics Institute John von Neumann Faculty of Informatics, Óbuda University
Budapest, Hungary
kovacs.levente@nik.uni-obuda.hu

***Abstract*—In many fields of the industry, like biology, medicine, power generation, chemical engineering, etc., where dealing with complex systems, the design of the control structure is a key factor. Designing robust and fault-tolerant controllers for these sophisticated processes has always been a challenging task. This paper discusses the design of a fault tolerant multi-agent system using fractional order controllers for level control in a three-tank system, which is very close to the hydrodynamic evolution of the isotope separation columns cascade, the final goal of the research. The fractional order controllers are designed using the Particle Swarm Optimization (PSO) method. The proposed architecture is implemented in JADE (Java Agent Development Environment) . The control structure is tested with good results on the laboratory equipment simulating different faults in the system.**

Keywords—control systems, fault-tolerant control, robust controller, fractional orderr controller, optimization, multi-agent system, biologically inspired control

I. Introduction

Multi-agent systems are widely used in the last decade for complex, cyber-physical systems. However, one major obstacle to the industrial deployment of multi-agent systems is their fault-tolerance deficiency. Being implemented across a network, such a system is vulnerable to external factors such as packet losses, nodes with disturbances, different transmission speeds, scheduling variations at each node and other parameters of the network. Ensuring that such a multi-agent system is safe involves a vast range of technologies. In [1] a distributed adaptive fault-tolerant leader-following consensus control scheme is present for a class of nonlinear uncertain multi-agent systems. In [2] the Takagi-Sugeno fuzzy models are used to describe the imprecise communication in the multi-agent system combined with a distributed adaptive iterative learning control. In [3] a sliding mode control is proposed to counteract the possible uncertainties in the multi-agent system. The review [4] discusses multi-agent models, focusing on synchronization, homogeneity, communication, topology, speedup, advantages and disadvantages.

Our goal in this paper is to use fractional order controllers [5] in the multi-agent system to counteract the model uncertainties. Fractional order PID controllers has two more degree of freedom in comparison with the classical, integer order controllers, which can be used in such a fault tolerant, multi-agent system [6-9]. The implementation of a fault tolerant control structure based on fractional order controllers is implemented by the authors in [10], while the developed multi agent control system is presented [11], based on TrueTime Toolbox in Matlab®. The present paper described the new results obtained with the combination of these two strategies and the implementation of the multi-agent structure is realized in Jade (Java Agent Development Environment).

The paper is structured in four parts. After this brief introductory part, section II describes the proposed control system. Section III presents the case study: the three-tank system and the last section of the paper ends with the conclusions.

II. The Control System

The proposed multi-agent control system is depicted in Fig.1. In this proposed structure model the independent agents are responsible for the active control of the assigned subsystem that executes the control algorithm based on the online received data from the sensors and on the received parameters from the supervisor agent. The redundancy of these agents is a software one, without overloading the physical structure of the system. The supervisor agent is responsible for detecting the faults, recalculating the control parameters and transmitting them to the independent agents in order to reach the global objective of the system.

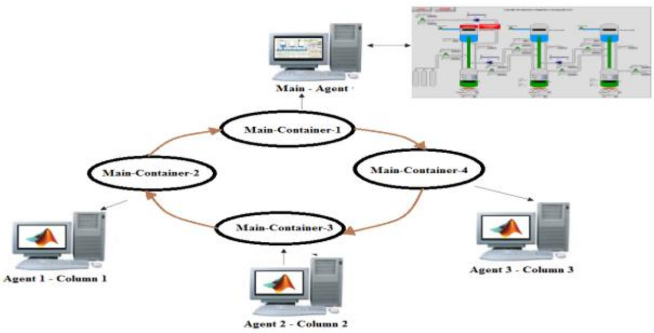

Fig. 1. The architecture of the fault tolerant, multi-agent control system

At this stage the realization of the proposed architecture is implemented in JADE [12]. This software was chosen because it offers support in different aspects of the development, as well as an environment in which the agents can exist and operate; classes constructed around the FIPA (Foundation for Intelligent Physical Agents) specifications; communication protocols and unique identification approaches in addition to a graphical interface, where the behavior of the agents can be monitored [12].

The communication is one of the most important aspects in the theory of the agents, as it permits to them to communicate their intentions or objectives. This stands at the base of this framework architecture.

The standards for the modeling of the agents were defined by FIPA, in which their communication and operation modes are specified. One of the most important is the Agent Communication Language (ACL), in which a standard language is defined through which the agents can share information according to the paradigms of the asynchronous communication.

The behavior of the agents is defined with the help of a special class named *ControlAgent*, which extends the base class *Agents* provided by Jade [12]. This class has fields for the parameters of the control function and the newly calculated coefficients are transmitted at each iteration step. As once initialized, the system should run uninterrupted. The class *CyclicBehaviour* was also extended to define the activities each agent has to carry out.

The fractional order controllers are designed using the Particle Swarm Optimization (PSO) algorithm [13, 14]. The transfer function of a fractional order controller is considered:

$$C_F(s) = K_P\left(1 + \frac{K_i}{s^{\lambda}} + K_d s^{\mu}\right) \tag{1}$$

The specific literature of PSO method [7, 8] uses cost functions based on minimum mean square error. The present paper deals with another approach, imposing the gain crossover frequency (ω_{gc}), phase margin (φ_m) and iso-damping property into the cost function (CF) in order to design the fractional order controllers [15]:

$$CF = |f_1(x)| + |f_2(x)| + |f_3(x)| \tag{2}$$

where

$$f_1 = K_P\sqrt{1 + K_i\omega_{gc}^{-\lambda}a + K_d\omega_{gc}^{\mu}b + 2\omega^{\mu-\lambda}K_iK_d\cos\left(\frac{(\lambda+\mu)\pi}{2}\right)} - \sqrt{\operatorname{Re}P^2(\omega_{gc}) + \operatorname{Im}P^2(\omega_{gc})}$$

$$f_2 = \frac{\omega_{gc}^{\mu}K_d\sin\left(\frac{\pi\mu}{2}\right) - \omega_{gc}^{-\lambda}K_i\sin\left(\frac{\pi\lambda}{2}\right)}{1 + \omega_{gc}^{\mu}K_d\cos\left(\frac{\pi\mu}{2}\right) + \omega_{gc}^{-\lambda}K_i\cos\left(\frac{\pi\lambda}{2}\right)} - \operatorname{tg}\left(-\pi + \varphi_m - \operatorname{arctg}\left(\frac{\operatorname{Im}P(\omega_{gc})}{\operatorname{Re}P(\omega_{gc})}\right)\right)$$

$$f_3 = \frac{c}{\left(1 + \omega_{gc}^{-\lambda}K_i\cos\left(\frac{\pi\lambda}{2}\right) + \omega_{gc}^{\mu}K_d\cos\left(\frac{\pi\mu}{2}\right)\right)^2} - \left.\frac{d\angle G_p(j\omega)}{d\omega}\right|_{\omega=\omega_{gc}}$$

$a = 2\cos\frac{\pi\lambda}{2} + K_i\omega_{gc}^{-\lambda}$, $b = 2\cos\frac{\pi\mu}{2} + K_d\omega_{gc}^{\mu}$ and P stands for the process transfer function.

As control strategy is applied the uncoupling, whereby each of the inputs is made to affect one output only. The MIMO (multi-input, multi-output) plant is controlled as a set of three SISO (single-input, single-output) plants, each acting independently of the others. The dependency between each SISO system is considered a disturbance, which is solved by the multi-agent strategy described in Fig.1

III. The Multi-Tank System

For testing the multi-agent fault tolerant system based on fractional order controllers, the MultiTank system was used which describes the frequent control problems met in the industry. The final goal of the research is to control the ^{13}C isotope separation columns cascade [16, 17, 18], which has a similar hydrodynamic evolution between The MultiTank system, Fig. 2, consists of four tanks, one as acting a buffer tank from which the rest of the installation is supplied, formed by three tanks connected in series [19]. Thus the faulty or incorrect functioning of the control system for one of the three tanks connected in series will lead to the destabilization of the rest of the subsystems' (tanks) functioning.

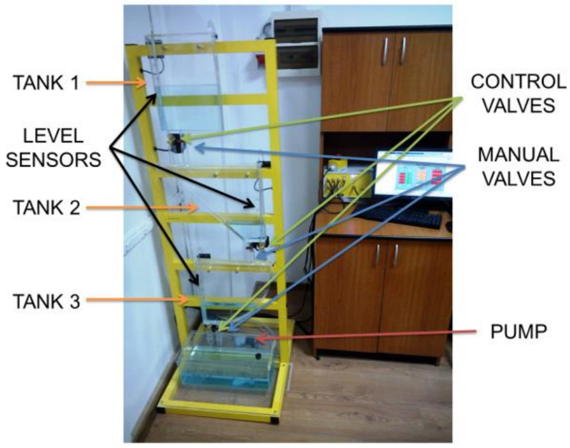

Fig. 2. The Multi-Tank System

The influence of the input values (pump, valves) over the output values (the levels in the three tanks) can be observed in Fig. 3.

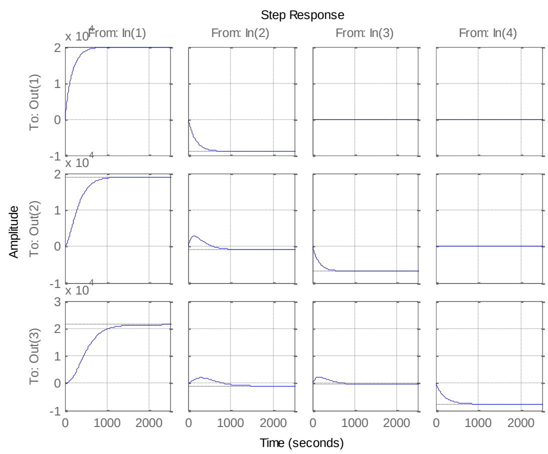

Fig. 3. The effect of the input over the process output values

For controller design the mathematic model of the system around the presumed stability point is used, derived from the mass balance equations:

$$\begin{cases} \frac{dV_1}{dt} = q - C_1\sqrt{H_1} \\ \frac{dV_2}{dt} = C_1\sqrt{H_1} - C_2\sqrt{H_2} \\ \frac{dV_3}{dt} = C_2\sqrt{H_2} - C_3\sqrt{H_3} \end{cases} \quad (3)$$

and

$$\begin{cases} \frac{dH_1}{dt} = \frac{1}{S_1}q - \frac{1}{S_1}C_1\sqrt{H_1} \\ \frac{dH_2}{dt} = \frac{1}{S_2}C_1\sqrt{H_1} - \frac{1}{S_2}C_2\sqrt{H_2} \\ \frac{dH_3}{dt} = \frac{1}{S_3}C_2\sqrt{H_2} - \frac{1}{S_3}C_3\sqrt{H_3} \end{cases} \quad (4)$$

where V_1, V_2, V_3 are the volumes of the fluids in the tanks, C_1, C_2, C_3 are the resistances of the output orifices, H_1, H_2, H_3 are the fluid level in thanks and q is the input flow.

IV. The Experimental Results

The next step was testing the proposed control system at simulation level before testing it in real-time on the installation itself. Therefore, on figures 4-7 the evolution of the command and the output signals can be observed for each tank in the system.

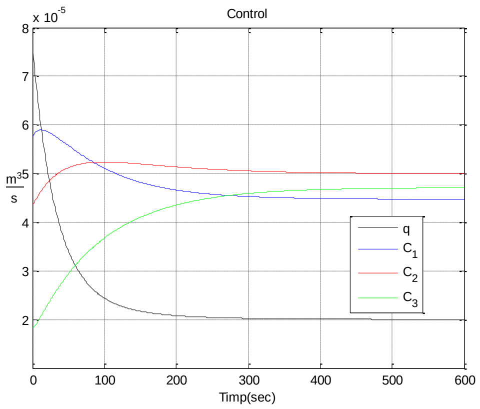

Fig. 4. The evolution of the command signals

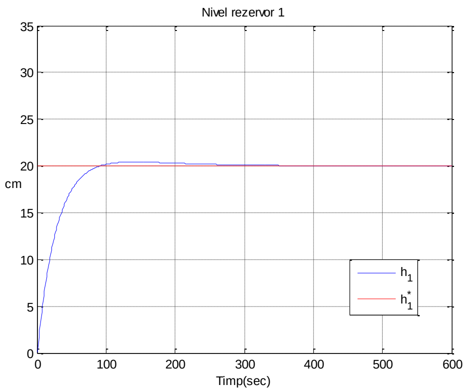

Fig. 5. The evolution of the level in the 1st tank

The last step for testing the proposed multi-agent system based on a fault tolerant, fractional order control is to test it in real time on the three-tank installation itself. In order to highlight the robustness of the control system using a fault tolerant, multi-agent system, the testing consisted of creating faults in the installation by opening the manual valves in different moments of time. Fully opening the manual valves in different periods of time (steady-state, transient state) and in different combinations (a valve belonging to a tank or all the valves) disturbances were induced in the whole system. The results of rejecting the effects of these disturbances are explained in the following.

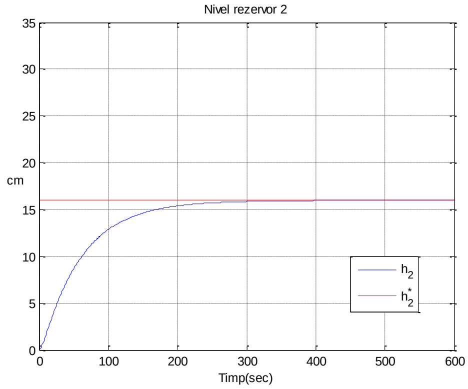

Fig. 6. The evolution of the level in the 2nd tank

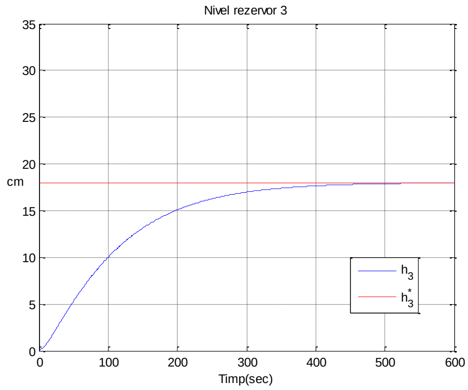

Fig. 7. The evolution of the level in the 3rd tank

Hence, in a first testing attempt, the opening of the manual valves was considered as a disturbance to the installation, both in transitory and steady state regime. The obtained results considering the appearance of the disturbance in the steady state are highlighted in Fig. 8-11.

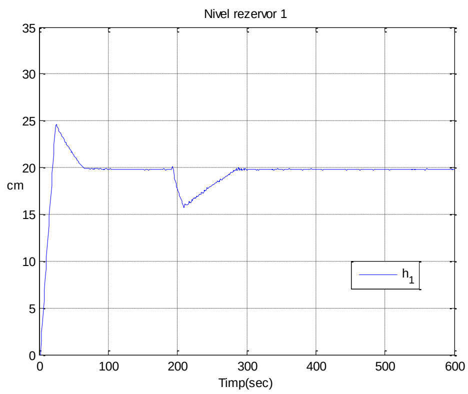

Fig. 8. Disturbance rejection in the 1st tank

In Fig. 8 the decrease of the level in the first tank can be observed, due to the opening of the manual valve. When the effect of the disturbance is detected, the controller increases the command signal of the pump (Fig. 9) until the level reaches again the desired value.

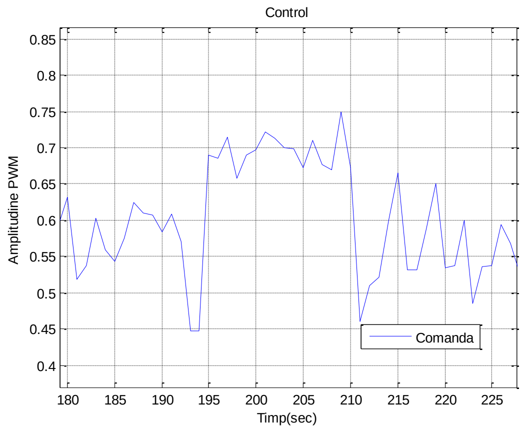

Fig. 9. The command signal of the DC motor pump

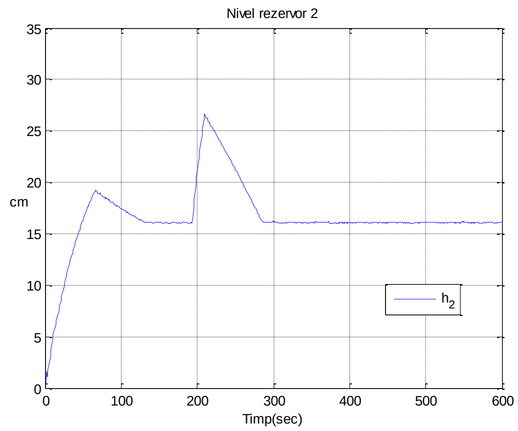

Fig. 10. Disturbance rejection in the 2nd tank

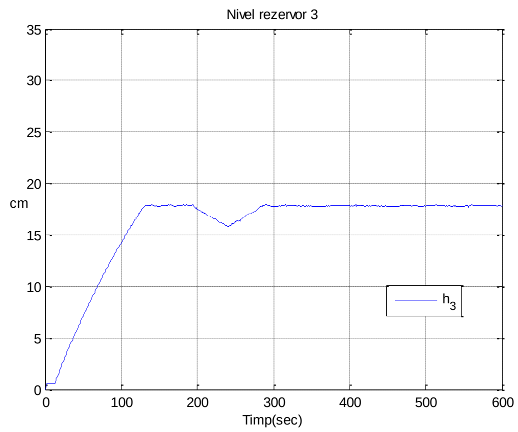

Fig. 11. Disturbance rejection in the last tank

On Fig. 10 the level in the second tank increases due to the opening of the manual valve between the first and the second tank, being heavily affected by the disturbance, but after that it returns to the set value. The level in the 3rd tank , Fig. 11, is the least affected.

The obtained results considering the appearance of the disturbance during the transitory regime are presented on Fig. 12-14.

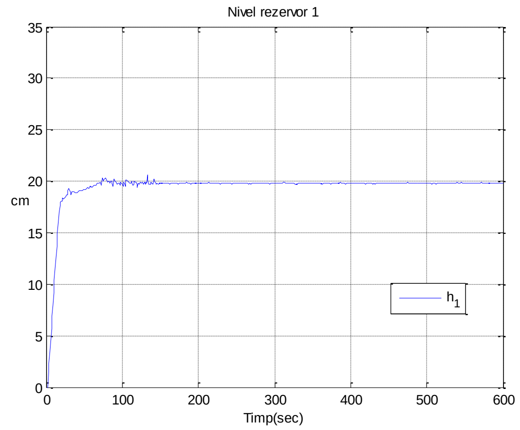

Fig. 12. Disturbance rejection during the transient state in the first tank

Inducing a disturbance in the transient state of the first tank, Fig. 12, an “improvement” of the process control can be observed in the case of the level in the first tank. The explanation to this is that in the normal functioning state of the process the inertia of the pump causes an overshoot that it is eliminated by the opening of the manual valve.

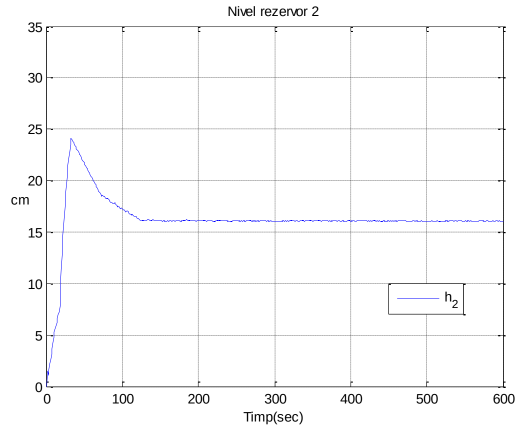

Fig. 13. Disturbance rejection in the second tank

The effect of the disturbance on the level in the last tank, Fig. 14, is only the slight increase of the settling time.

Opening the manual valve between the second and the third tank brings significal disturbances over the control system in steady state functioning. Therefore, in the second attempt of testing, the manual valve mentioned above was considered as a disturbance of the system. The effects of the disturbance are: the volume of the liquid in the second tank decreases, thus the first control valve opens and the flow generated by the pump increases.

The obtained results considering the appearance of the disturbance in the steady state are presented in Fig. 15-17. The effect of the opened manual valve is significant in the second,

Fig. 15, and in the third tank, Fig. 16, and less significant for the first one, Fig. 17. The level in the third tank increases as the valve is opened.

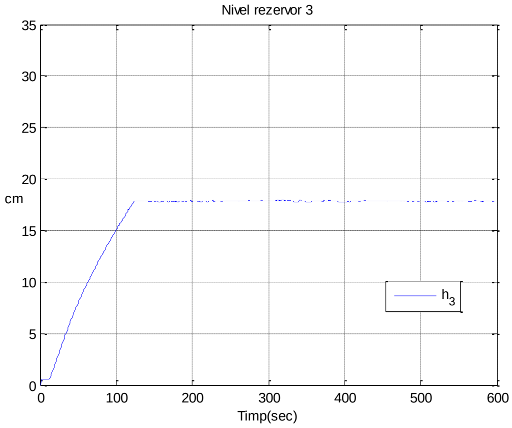

Fig. 14. Disturbance rejection in the last tank

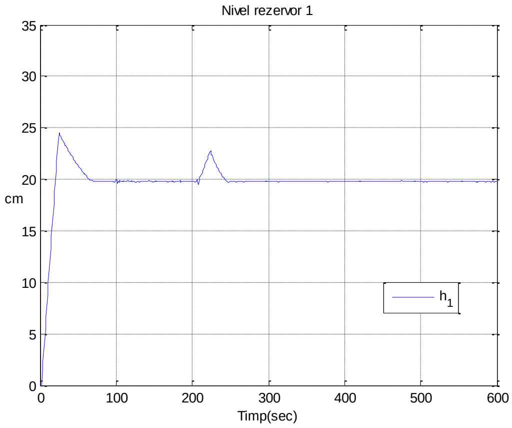

Fig. 15. Disturbance rejection in the first tank

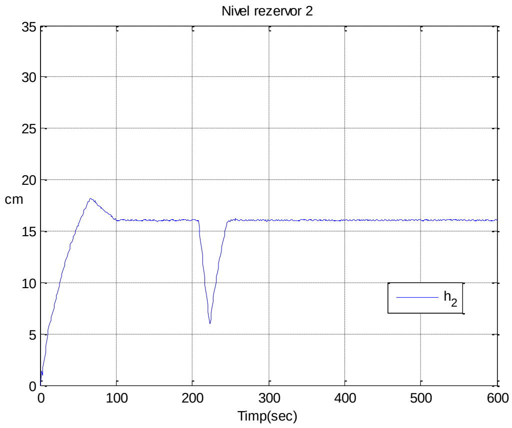

Fig. 16. Disturbance rejection in the second tank

In the third attempt of testing, multiple simultaneous disturbances were considered for more subsystems. In this way multiple disturbances were generated by opening all the manual valves of the MultiTank system simultaneously both in transient and steady state. The obtained results, considering the appearance of the disturbances in the steady state are presented in Fig. 18-21. The obtained results, considering the appearance of the disturbances in transient state are shown on Fig. 22. In transient state, the effect of opening the manual valves is very small, only influencing the way in which it reaches the steady state.

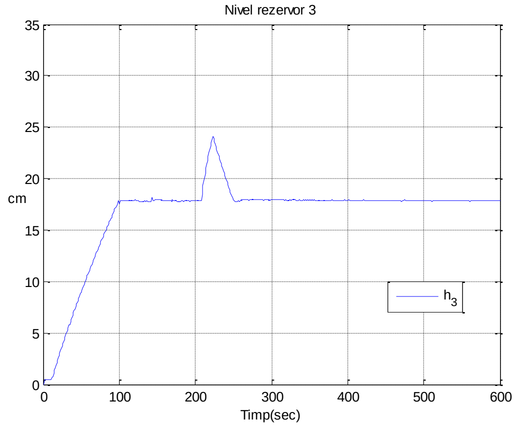

Fig. 17. Disturbance rejection in the third tank

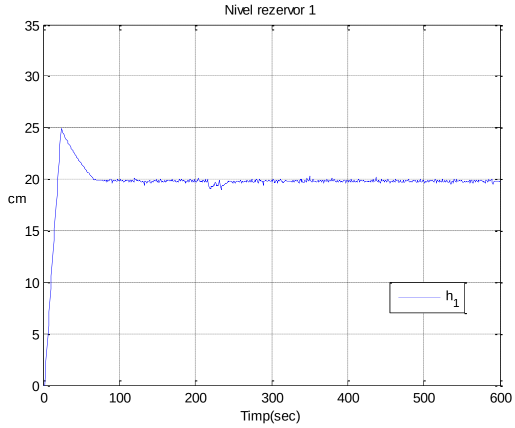

Fig. 18. The experimental results for the first tank considering multiple disturbances

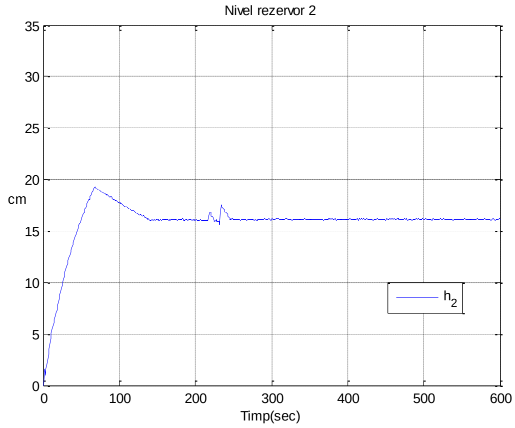

Fig. 19. The experimental results for the second tank considering multiple disturbances

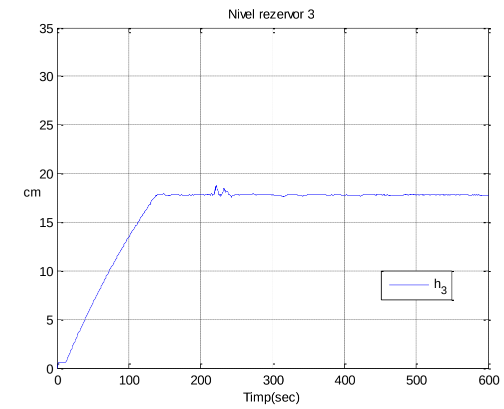

Fig. 20. The experimental results for the third tank considering multiple disturbances

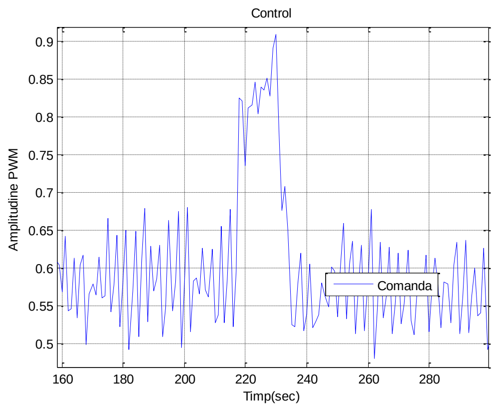

Fig. 21. The control signal for the DC motor of the pump considering multiple disturbances

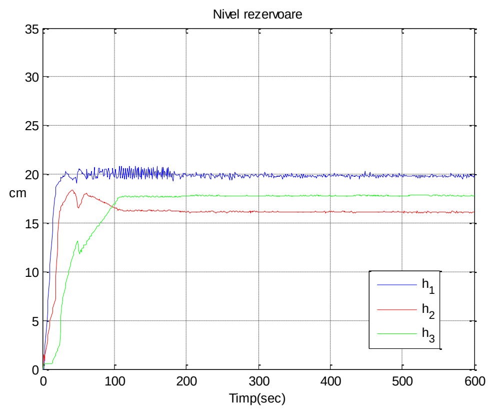

Fig. 22. The experimental results of all the levels in all three tanks considering multiple disturbances

CONCLUSIONS

The work deals with the fault tolerant control system design of a MIMO system having sensors and actuators as agents. The used controllers are designed to be robust to gain variations while the fault tolerance of the system is ensured by communication between the immediate neighbours of the agents and in the case of a critical failure, this neighbour can take over the roles and responsibilities of the faulty element. The case study is a laboratory scale three-tank system. The experimental results prove the efficiency of the proposed control strategy, having combined the advantages of a fault tolerant control structure and the advantages of the fractional order controllers.

ACKNOWLEDGMENT

This work was supported by the Janos Bolyai grant of the Hungarian Academy of Sciences.

REFERENCES

[1] M Khalili *et all*, Distributed adaptive fault-tolerant control of uncertain multi-agent systems, *Automatica*, 2018, 87: 142-151.

[2] J. Chen, Li J., Fuzzy adaptive iterative learning coordination control of second-order multi-agent systems with imprecise communication topology structure, *International Journal of Systems Science*, 2018, 49(3): 546-556.

[3] J. Yhang *et al.*, Sliding Mode Control for a Class of Nonlinear Multi-agent System with Time Delay and Uncertainties, *IEEE Transactions on Industrial Electronics*, 2018, 65(1): 865-875.

[4] Y.-J., Gong *et al.*, Distributed evolutionary algorithms and their models: A survey of the state-of-the-art, Applied Soft Computing Journal, 2015, 34(4): 286-300.

[5] I. Podlubny, Fractional-order systems and PIλDμ-controllers, *IEEE Transactions on Automatic Control*, 1999, 44:208-214.

[6] CI Muresan, Dulf EH, Both R., Vector Based Tuning and Experimental Validation of Fractional Order PI/PD Controllers, *Journal of Nonlinear Dynamics*, 2016, 84(1):179-188.

[7] CI. Muresan, Dutta A, Dulf E H et al., Tuning algorithms for fractional order internal model controllers for time delay processes, *International Journal of Control*, 2016, 89(3): 579-593.

[8] EH Dulf , Dulf FV, Pop CI, Fractional Model of the Cryogenic (^{13}C) Isotope Separation Column, *Chemical Engineering Communication*, 2015, 202(12):1600-1606.

[9] EH Dulf, Muresan CI, Unguresan M L, Modeling the (^{15}N) isotope separation column, *Journal of Mathematical Chemistry*, 2014, 52(1):115.

[10] EH. Dulf et al., Fault tolerant distributed control system with robust fractional order controllers, 2016 IEEE International Conference on SMC, DOI: 10.1109/SMC.2016.7844615

[11] EH. Dulf et al., Robust Fractional Order Controllers for Distributed Systems, *Acta Polytechnica Hungarica*, 2017, 14(1):163-176

[12] C. Robinsont all. MACSimJX: A Tool for Enabling Agent Modelling with Simulink Using JADE, *Journal of Physical Agents*, 2010, 4(3): 1-7.

[13] M. Couceiro, Ghamisi Pedram, Fractional Order Darwinian Particle Swarm Optimization. Applications and Evaluation of an Evolutionary Algorithm, *SpringerBriefs in Applied Sciences and Technology*, ISBN 9783319196350, 2016

[14] R. Eberhart, J. Kennedy, A new optimizer using particle swarm theory, *Proceedings of the 6th International Symposium Micro Machine and Human Science* (MHS), 1995, 39–43.

[15] E.H. Dulf, D. Timis, C.-I. Muresan, Robust Fractional Order Controllers for Distributed Systems, *Acta Polytechnica Hungarica*, 2017, 14(1):163-176.

[16] E.H. Dulf, C.I. Pop, F.V. Dulf, "Fractional calculus in C13 separation column control", Signal, Image and Video Processing, 2012, 6:479-485

[17] E.H. Dulf, F.V. Dulf, C.I. Pop, "Fractional Model of the Cryogenic (^{13}C) Isotope Separation Column", Chemical Engineering Communication, DOI: 10.1080/00986445.2014.968709, Volume 202, Issue 12, 2015

[18] Inteco, MultiTank System-User's Manual, 2008. Available at www.inteco.com.pl