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Redesign of the Research Platform for Monitoring, Control and Security of Critical Infrastructure Systems

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***Abstract*—Critical Infrastructure Systems (CISs) play a key role in modern societies. Their sustainable operation depends heavily on the performance of dedicated structures and algorithms targeting monitoring, control and security aspects. In previous work a Research Platform (RP) for the design and simulation of such systems was presented. This works updates the information on the RP through the description of major hardware and software updates made. An example illustrating how this is to serve to include undergraduate students into research work is included.**

***Keywords*—Multiagent control, Multiagent environment, Simulation, Critical Infrastructure Systems, Hardware in the Loop.**

I. Introduction

For more than the last ten years a class of a Large Scale Complex Systems (LSCSs), namely Critical Infrastructure Systems (CISs) has gained significant attention in the scientific community [1]. This is due to growing dependency of the modern society on the continuous access and sustainable performance the CISs. Representative examples of CISs are the: Drinking Water Distribution Systems (DWDSs), electric power, and telecommunication systems, social networks and cities considered now a most complex of the CISs which interlinks the former with (tremendously) complex interactions. Nowadays, these systems constitute the environment in which humans undertake their daily routines. This is the fact which makes the CISs affect not only the quality of life but tend to determine (impact) the security of human health and (even) human life itself. In consequence, establishing a reliable monitoring and control, including security aspects (especially after the 9/11), is considered essential. However, due to the complexity of the CISs interactions and each of the system on its own the development of the required structures and algorithms to perform the above-mentioned tasks is complex and requires an adequate set of tools. Due to the nature of the CISs (i.e. continuity of service) the access to the physical plant for algorithm development and testing is quite limited. This calls out for the use of appropriate simulation tools which under these circumstances are essential.

In previous research works the problems of monitoring, control, and security of DWDS-CIS were addressed. For example in [2] a problem of water quality modelling was addressed and state-of-the-art water quality model was developed. Consequently, a security module was introduced to extend the above-mentioned water quality model capabilities to handle the security operational states in [3] . The models and algorithms for monitoring were developed and tested in [4]. Models for robust model-based predictive control were considered in [5]. A problem of joint control system design and actuator system allocation was considered for a DWDS system in [6]. The problems of CIS monitoring, control, and security systems design were comprehensively introduced in [7]. The structure and algorithms given in the above-mentioned works were designed and tested using a dedicated Research Platform (RP) [8]. The key features of the RP were designed to handle the Multi Agent (MA) type algorithms and issues related to the field of control engineering, which as indicated in [8], can, in fact, be completely different from the concepts known form the field of IT. In the latter case, the MA systems are deployed as 'swarm of atomic agent' that perform basic computational operations. In the former case, the computational tasks are quite large e.g. monitoring or control of a given sector of a DWDS which is considered a natural 'atomic' behaviour of a control engineering based agent [7]. This short comparison gave an intuitive sense of the difference apart from the technical issues of e.g. bandwidth of communication links [8]). Five years have passed and the RP has 'grown' to be a mature tool, highly capable to serve its purpose. However, some improvements had to be made due to the observed drawbacks of the oroginal design. The main drawbacks identified up to date are related to the software and in terms of RP availability and the rather high level of entry requirements for the RP users. In order to cope with these issues, some hardware and software modifications had to be made. The result is that at this point the RP can serve as a system prototyping environment for both highly complex systems as well as it enables to include undergraduate students in the research activities as well.

At this point it should be noted that the paper does not introduce any new IT solution nor a theory. The contribution of this paper is that it updates the proposition of RP for Multi Agent system development which was initially document in [8]. The update is both in the hardware and software configuration. The level of entry for the potential user is now have been considerably lowered to enable one to invite the undergraduate students to participate in the research activities. And possibly the information and experience described in the paper have a potential to save one's time and effort when choosing an appropriate environment to serve ones purpose.

The paper is organised in the following manner. In Section II the previous RP configuration is briefly given and the extensions made are indicated. Following, in Section III a case study system is introduced. In Section IV a numerical example is given to simply illustrate the redesigned RP features. Section V concludes the paper.

II. Research platform

The section is organised in the following manner. In Subsection II-A the previously existing RP basis is shortly characterised in accordance to [8]. Consequently, in Subsection II-B a configuration update is introduced and justified in order for the up-to-date RP description to be complete.

A. The basis

1) Hardware: In principal, the RP is a set of three high-performance computational units and complimentary devices set up to enable the hardware-in-the-loop computation. Each of the computer units is equipped with: Intel I7 CPU (4 core, Hyper Threading (HT) enabled), 8 GiB of Random Access Memory (RAM), 1 TB of available hard drive disk space for storage purposes and CUDA graphic card for GPU computing. Each computer has been also equipped with serial ports (RS232) and I/O cards to enable external device communication. The computer units are enclosed in the RACK chassis. The communication links are established with Fast Ethernet connections over a managed switch. The Internet connection has been granted via router in order to isolate the RP network. This enabled fast data exchange in between the RP computational units. The manageable switch included in the network allows one to establish and test variety of communication scenarios. The platform is extended by two additional computational units (dual-core, 8 GiB RAM, GPU computing enabled) to serve as either workstations or computational units when required.

2) Software: As indicated in previous work a state-of-the-art tool — JADE, a JAVA based software package developed by Italian Telecom (TILab), was used for MA system and software communication. The JADE software is supported by the numerous applications by i.e. Fraunhofer Institut fur Informations und Datenverarbeitung, French National Institute of Research in Computer Science and Control (INRIA) and Rockwell Automation. The benefits of its use are i.e. included tools for system management and maintenance, advanced agent migration capabilities and possibility to create advanced 'language' communication schemes based on message type recognition tools. This allows one to handle the MA system spread over local and remote computational units [8].

In previous works, the MATLAB software extended with Tomlab software package has been selected as a core for the MA system development and testing as well as computational purposes [8].

In order to handle the simulation of DWDSs the EPANET USEPA [9] software package and EPANET-MSX add-on [10] have been selected due to its wide community recognition and the fact that it is a public domain tool. These two tools combined allow one to perform efficient simulation of both hydraulic and (bio-) chemical processes that occur in the case-study system.

A PostgreSQL database was selected to establish the postulated data exchange mechanisms [8].

A fine-tuned Windows 7 operating system used to host the describes software tools and establish device communication base [8].

For the overall MA system a dedicated XML based configuration mechanism was developed to enable fast and convenient system start-up [8].

The described in [8] RP was developed to work with internal time that is the subsequent computational cycle is started one after another.

The information exchange structure is illustrated in Fig. 1.

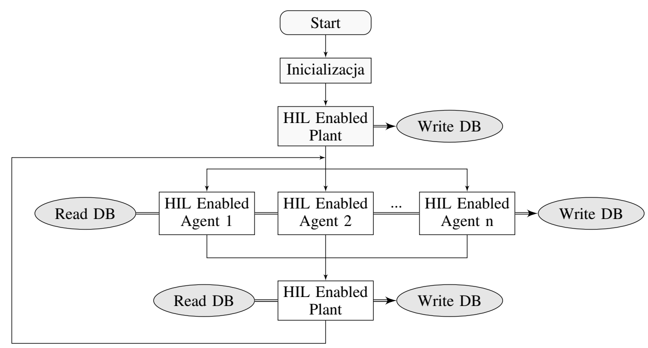

Fig. 1. Research platform

B. Modifications

1) Hardware: The RP was equipped with (up to five, included as needed) NI Elvis II platforms to extend its hardware-in-the-loop capabilities (Fig 2 — 'Hardware-in-the-Loop (HIL) Enabled Agents'). The most important benefit (apart of the platform 'robustness' and considerably large mean-time between failures) is its ease of use and programming and possibility to include extension boards that can drastically modify the platform functionality while maintaining standardised communication interfaces. Moreover, the ease of use and programming allows one to invite undergraduate students to take part and contribute to more sophisticated research en devours as illustrated by the example given in following sections.

2) Software: Fundamentally, a process of shifting the base operating system from Windows to Linux has been completed over all major nodes. The new software components introduced are the LabVIEW graphical programming language that natively supports the NI Elvis II platform and Python for both Elvis II communication and rapid algorithm development. However, based on the recent experience with the software tools there is a strong notion to reduce (or even rule out) the LabVIEW component and make the MATLAB and Python interchangeable at all considered RP levels.

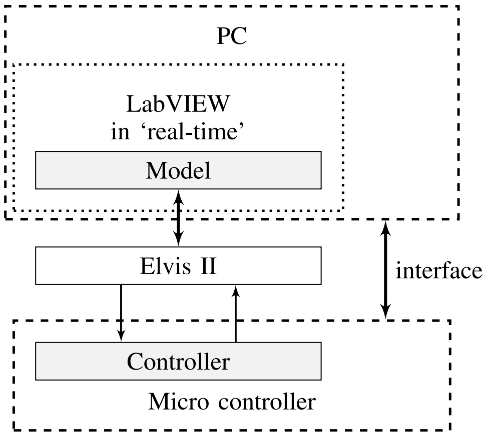

Fig. 2. Hardware-in-the-loop using NI Elvis II

III. Case study DWDS

An illustrative case study DWDS has been depicted in Fig. 3. The model is a modified case study example presented in [11]. It is comprised of 10 nodes indicated by dots and 12 links. The considered nodes include: the source node (denoted 'Reservoir and pump'), storage node ('Tank') and 8 consumer demand nodes (indicated by numbers 2 – 8). Links are to represent the interconnection piping of the DWDS. Therefore, the depicted network scheme graphically represents the hydraulic model of the DWDS. The modification is introduced by including a control valve in between the nodes 'Tank' and 3 and the reason for that is explained in the following paragraphs.

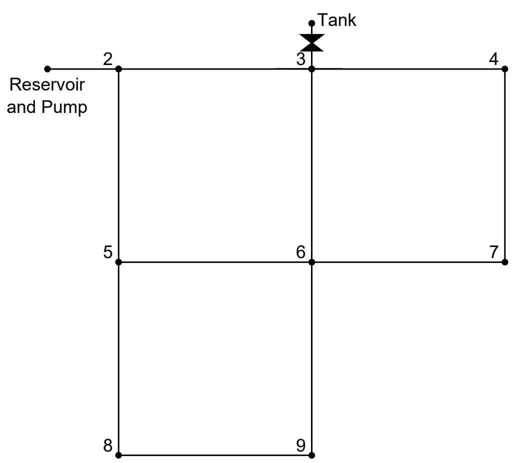

Fig. 3. DWDS example

The quality model, namely the part describing the chemical, biological and the bio-chemical processes are given by the state-of-the-art model introduced in [2] and depicted in Fig 4. It comprises two main modules addressing the DWDS water 'Chemistry' and 'Biological regrowth and nutrients' as well as the interaction layer that includes the bio-chemical processes. The quality model has been enhanced with a so-called 'Security module' (Fig. 5) to account for the water security threatening events — including the malicious attacks on the CIS by intended contamination [3]. The derived quality model and its extension have been implemented for simulation purposes using EPANET-MSX add-on [10].

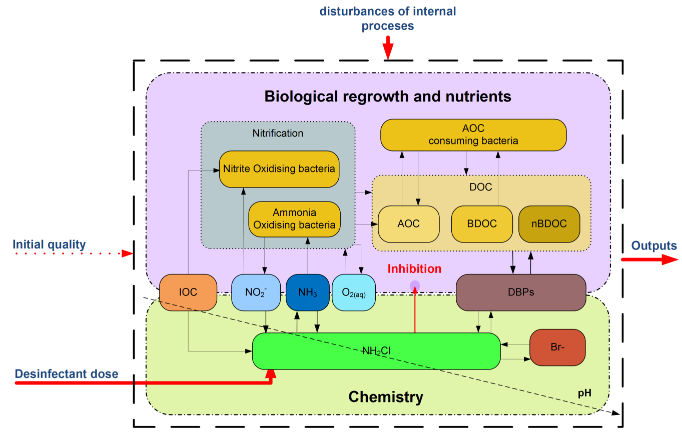

Fig. 4. Cognitive DWDS quality model

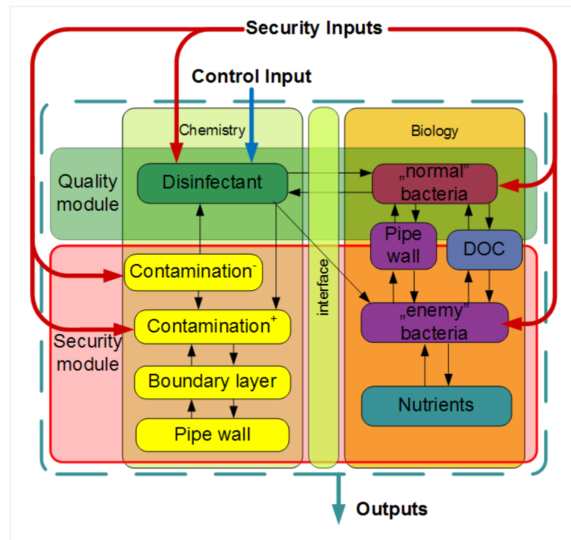

Fig. 5. Security module

It should be noted that the proposed modification is a simple and cost effective solution proposed as a result of previous research and is to serve two purposes. First is a network pressure control. Second is for the security reasons as the 'Tank' node is most vulnerable part of this DWDS as it has been indicated in [3].

IV. Numerical example

At this point the benefits of the proposed RP modifications are indicated. Following the hierarchical control system structure that is obtained by functional or temporal system decomposition the valve stem control system resides in the so-called direct control layer e.g. [12]–[15]. The DWDS-wide hydraulic control system is therefore to prescribe the reference valve stem position to the dedicated valve control algorithm in order to apply the control actions required for the hydraulic balance to be maintained e.g. [16]. The role of the valve control system is therefore to track the prescribed reference signal with required performance and execute the control. This is a typical positioning problem that can be solve using e.g. classical control tools. This in fact can be handled by undergraduate students. An example of such project exploiting the 'V-model' design framework (Fig. 6) is presented.

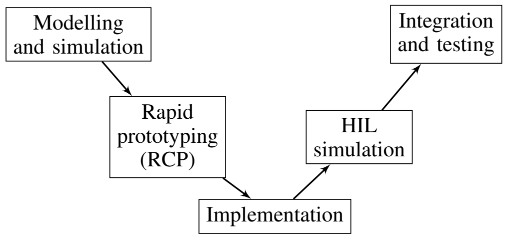

Fig. 6. 'V-model'-based design work-flow

The approach follows the consequent steps of: process 'Modelling and simulation', 'Rapid control algorithm prototyping', 'Implementation' 'HIL simulation' and 'Integration and testing'. It should be noted that the provided in the following paragraphs example is a part of the research results submitted by two of the authors (enlisted last) as a partial requirement to obtain the B.Sc. in Control Engineering (graduated in 2018).

A. Plant model

1) Model structure: Let the model of a motor driving a valve stem be given by:

$$L_{\mathrm{w}}\frac{\mathrm{d}i_{\mathrm{w}}}{\mathrm{d}t} = u_{\mathrm{w}}(t) - R_{\mathrm{w}}i_{\mathrm{w}}(t) - K_{\mathrm{e}}\omega(t) \tag{1a}$$

$$J_{\mathrm{s}}\frac{\mathrm{d}\omega(t)}{\mathrm{d}t} = K_{\mathrm{m}}i_{\mathrm{w}} - T(\omega(t)) \tag{1b}$$

where: L_{w} denotes armature's inductance [H], $i_{\mathrm{w}}(t)$ is the armature current [A], $u_{\mathrm{w}}(t)$ denotes the voltage applied to the motor's armature [V], R_{w} is the armature's resistance $[\Omega]$, K_{e} is the electromotive force constant $[\mathrm{V\,n/min}]$, $\omega(t)$ denotes the rotational velocity of the shaft $[\mathrm{n/min}]$, J_{s} is the moment of inertia of the motor's armature and load combined $[\mathrm{kg\,m^2}]$, K_{m} is the motor torque constant $[\mathrm{N\,m/A}]$ and $T(\omega(t))$ denotes the friction torque $[\mathrm{N\,m}]$, which is considered to be given by [17], [18]:

$$T(\omega_{\mathrm{s}}) \stackrel{\mathrm{def}}{=} \sqrt{2e}T_{\mathrm{brk}}\exp\left(-\left(\frac{\omega(t)}{\omega_{\mathrm{st}}}\right)^2\right)\frac{\omega(t)}{\omega_{\mathrm{st}}} + f\omega(t), \tag{2}$$

where: e is the Euler's constant, T_{brk} denotes the breakaway friction torque $[\mathrm{N\,m}]$, ω_{st} is the Stribeck velocity threshold $[\mathrm{n/min}]$ and f is the viscous friction coefficient $[\mathrm{Nmn/min}]$.

It should be noted that the friction model (2) accounts for the effects of the transmission gear by adequate parameter identification. Therefore, the model of the transmission gear is assumed to be given by a static proportionality factor. Moreover, in the scope of this example it is assumed that: the internal dynamics of the actuator system (motor power supply) are considerably faster and can be neglected; the available measurement information on position and velocity is perfectly known.

2) Parameter identification: The parameter identification procedures used in the scope of the presented example utilise both simple calculation and optimisation based techniques in order to acquire the required piece of information.

a) Resistance R_{w}: The identification data was collected in the form of input voltage $u_{\mathrm{w}}(t)$ – output current $i_{\mathrm{w}}(t)$ data pairs assuming $u_{\mathrm{w}}(t) = const$ and $\omega(t) = 0$. Using (1a) and the collected data samples allowed one for the identification of the value of R_{w}.

b) Inductance L_{w}: In order to identify L_{w} a technical method of impedance measurement was applied. This together with already known R_{w} allowed to calculate the armature reactants and in consequence the inductance L_{w} which completed the experiment.

c) Electromotive force constant K_{e}: The measurement data was collected by shifting the motor operating state into the generator mode by applying a reference momentum to the motor shaft. The collected data and (1a) allowed to identify the K_{e}.

d) Motor torque constant K_{m}: The identification data set comprised of the armature current $u_{\mathrm{w}}(t)$ – shaft stall $(\omega(t) = 0)$ momentum under different motor power supply voltage levels. The data together with (1b) allowed to identify K_{m}.

e) Linear gain of friction model f: The parameter f was identified based on the two distinct measurement data samples. Each sample comprised of a rotational velocity $\omega(t)$ and corresponding armature's current $i_{\mathrm{w}}(t)$ acquired at steady state.

f) Gain of nonlinear part of friction model T_{brk}: The friction model parameter T_{brk} has been identified based on the static characteristic $\omega\left(u_{\mathrm{w}}\right)$ of the plant which allows one to identified the armature's input voltage level required to break the static friction momentum and in consequence derive the value of friction model parameter T_{brk}.

g) Stribeck velocity ω_{st}: The problem of ω_{st} identification was formulated in terms of minimising the ℓ^2-norm of error in between the plant and model based static characteristic.

h) Load moment of inertia J_{L}: The problem of J_{L} identification was formulated in terms of minimising the ℓ^2-norm of error of in between the plant and model step response.

It should be noted that both considered optimisation tasks (addressing the ω_{st} and J_{L}) were formulated in discretised (sample based) domains.

B. Control system and RPC

1) Structure and algorithms: In order to guaranty an adequate control system performance a double loop output feedback (cascade-like) structure has been selected to tackle the task at hand. The PID based control algorithms have been selected to handle both feedback loops with PI type controller in the inner and P type controller in the outer loop, respectively (Fig. 7). Moreover, due to the acting integral term the inner loop controller has been equipped with a static (back-calculated) anti-windup filter.

2) Parameter tuning: Assuming zero initial conditions and taking $G(s)$ to denote a ration of the Laplace transform of the $\omega(t)$ to the transform of $u_{\mathrm{w}}(t)$ yields:

$$G\left(s\right) = \frac{K_{\mathrm{m}}}{J_{\mathrm{s}}L_{\mathrm{w}}s^2 + \left(R_{\mathrm{w}}J + fL_{\mathrm{w}}\right)s + R_{\mathrm{w}}f + K_{\mathrm{m}}K_{\mathrm{e}}}. \tag{3}$$

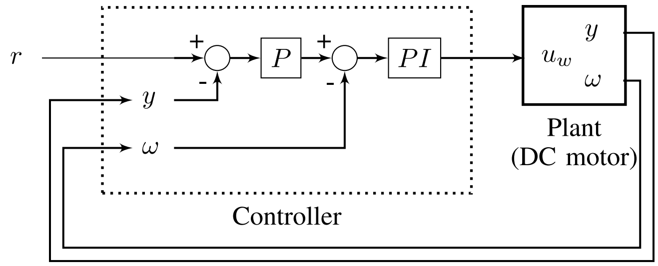

Fig. 7. Closed loop control structure

Reducing the order of (3) by neglecting the fastest time constant and rewriting the result in the closed loop format by following the scheme given in Fig. 7, including the operator transfer function, yields:

$$G_{\mathrm{CL}}(s) = \frac{\frac{ak_{\mathrm{p\,PI}}k_{p\,\mathrm{P}}}{b}s + \frac{ak_{\mathrm{i\,PI}}k_{p\,\mathrm{P}}}{b}}{s^3 + \frac{1+ak_{\mathrm{p\,PI}}}{b}s^2 + \frac{ak_{\mathrm{i\,PI}}+ak_{p\,\mathrm{P}}k_{\mathrm{p\,PI}}}{b}s + \frac{ak_{\mathrm{i\,PI}}k_{p\,\mathrm{P}}}{b}} \tag{4}$$

where: $a = \frac{K_m}{R_w f + K_m K_e}$, $b = \frac{R_w J_s + f L_w}{R_w f + K_m K_e}$. Arranging the closed loop poles at $s_0 = -16$, $s_1 = -16.5$, $s_2 = -17$ yields the control system parameters as described in Section IV-E.

C. Implementation

The prototype algorithms were emulated into discrete time using Tustin discretisation method and deployed using Arduino Mega 2560 (as a proof-of-concept environment) for HIL simulation (using the setup depicted in Fig. 2) and following deployment.

D. Control application

First, the designed control system was translated into C code and implemented within the Arduino hardware platform for HIL testing. In ordered to perform this step the plant (motor) model (1) with (2) has been implemented using LabVIEW (graphical) programming language for real-time simulation. This allowed the authors to fine tune the control system parameters including the discretisation time. The HIL enabled authors to correct the latter due to Arduino limited computational efficiency largely depleted due to I/O communication (though without violating the law of Shannon – Kotelnikov). Second, the derived physical Arduino based controller equipped with designed and fine-tuned control algorithm has been coupled with the plant, namely the DC motor. The work done while tackling the previous stages based on the 'V-model' design made the task elementary and the results obtained have been found to coincide with the predictions made as described in the following subsection.

E. Results

1) Parameter identification: In principal, the results of the model parameter identification have been given by the first two row groups in Table I.

2) Controller rapid prototyping: The results of the control system RPC have been given in the last row group given of Table I.

TABLE I. IDENTIFIED MOTOR PARAMETERS

	Parameter	Value	Unit
Motor model	R_{w}	$3.2 \cdot 10^{0}$	Ω
	L_{w}	$2.0 \cdot 10^{-2}$	H
	K_{e}	$6.8 \cdot 10^{-2}$	V n/min
	J_{s}	$9.6 \cdot 10^{-4}$	kg m^2
	K_{m}	$1.9 \cdot 10^{-1}$	N m/A
Friction model	T_{brk}	$1.0 \cdot 10^{-1}$	n/min
	ω_{st}	$1.0 \cdot 10^{0}$	n/min
	f	$4.2 \cdot 10^{-5}$	Nm · n/min
Controller	$k_{p\,\mathrm{P}}$	$5.3 \cdot 10^{2}$	n/(min · rad)
	$k_{\mathrm{p\,PI}}$	$7.1 \cdot 10^{-1}$	V min/n
	$k_{\mathrm{i\,PI}}$	$8.3 \cdot 10^{0}$	s V min/n
	$k_{\mathrm{AW\,PI}}$	$8.8 \cdot 10^{0}$	n/(min V)

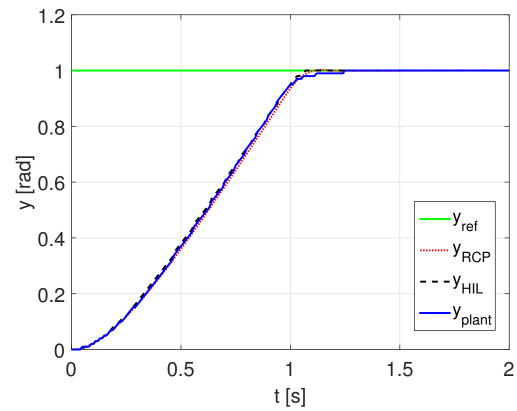

Fig. 8. Position in step response experiment

3) HIL simulation and deployment: Addressing the results of the closed loop system performance obtained in model simulation, HIL and deployment given in Figs. 8 – 10 it has been found that the proposed additional hardware and software infrastructure included in RP is adequate and the results are (mostly) satisfactory. The observed in the example drawbacks are in the motor rotational velocity predictions during HIL simulation. At this point it is hypothesised that the observed phenomena are occurring due to: inefficient numerical procedures used to handle the friction in HIL plant simulation module, transmission lags over the PC – NI Elvis II communication channel established via universal serial bus and modelling errors i.a. measurement noise and discretisation error which have been neglects in this work.

The observed system behaviour can be quantified by analysing the closed loop system signals, namely the position, velocity and control input, with respect to physical system deployment, in terms of ℓ^1, ℓ^2 and ℓ^∞ norms. The values of the selected measures (obtained for signals as illustrated in Figs. 8 – 10) are given in Table II. The obtained values of the ℓ^1 and ℓ^2 norms clearly indicate that the HIL behaviour represents the deployed system behaviour more accurately than the Rapid Prototyping (RPC). However, this is not the case in terms of ℓ^∞. This results justify the hypotheses given in previous paragraph.

V. CONCLUSIONS

In the scope of this work a description of the Research Platform for multi-agent monitoring, control and security of Critical Infrastructure System has ben given in terms of its recent development. The goal of this work is to illustrate the

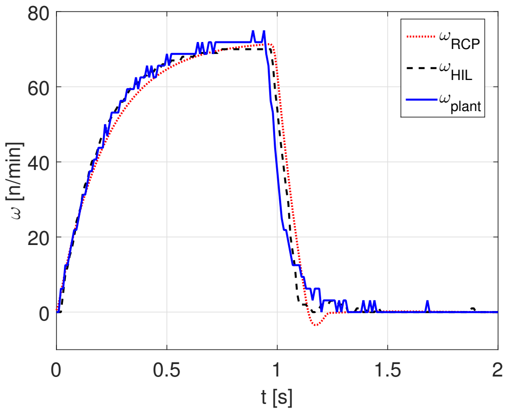

Fig. 9. Velocity in step response experiment

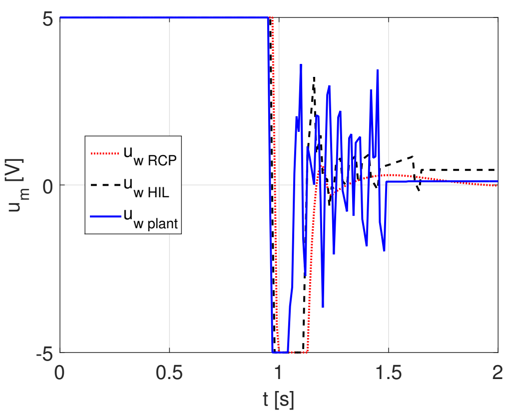

Fig. 10. Control input in step response experiment

advancements and share the experience gained to possibly help with ones choices to be made and save time where possible. Technically, though no new hardware or software was introduced the authors did share some thoughts on the experience gained while using different set of tools and their configuration. The main advantages of the extensions made is towards enabling the open source software solutions, real-time (HIL) and above all showing a possible mechanism of how to include the undergraduate students 'in-the-loop' of advanced research.

The future work in the subject is set toward extending the HIL capabilities and investigating the potential behind the private cloud and cloud services solutions.

VI. Acknowlegments

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TABLE II. Closed loop system signal comparison

		ℓ^1	ℓ^2	ℓ^∞
y	RCP	$5.6e-3$	$7.1e-5$	$2.4e-2$
	HIL	$4.3e-3$	$4.9e-5$	$5.0e-5$
ω	RCP	2.7	31	9.7
	HIL	1.9	14	11
u_w	RCP	0.63	2.7	8.6
	HIL	0.61	2.0	8.6

References

[1] IntelliCIS, "COST ACTION IC0806 – IntelliCIS. Memorandum of Understanding," 7th Framework Program, European Commission, Brussels, Dec. 2008. [Online]. Available: http://www.cost.esf.org

[2] K. Arminski, T. Zubowicz, and M. A. Brdys, "Biochemical multi-specie quality model of drinking water distribution system for simulation and design," *International Journal of Applied Mathematics and Computer Science*, 2013.

[3] T. Zubowicz, K. Arminski, and M. A. Brdys, "Quality model for integrated security monitoring and control in water distribution systems," in *10th World Congress on Intelligent Control and Automation – WCICA 2012*, Beijing, China, Jul. 2012.

[4] K. Arminski and M. A. Brdys, "Robust monitoring of water quality in drinking water distribution systems," in *Large Scale Complex Systems Theory and Applications*, Y. Xi, Ed., vol. 10, Shanghai, China, Jul. 2013, pp. AA–CC.

[5] M. A. Brdys, T. Zubowicz, and K. Arminski, "Robust parameter estimation and output prediction for reactive carrier-load nonlinear dynamic networks," in *Large Scale Complex Systems Theory and Applications*, Y. Xi, Ed., vol. 10, Shanghai, China, Jul. 2013, pp. 426–431.

[6] G. Ewald, T. Zubowicz, and M. A. Brdys, "Optimised allocation of actuators for dwds," *Journal of Process Control*, vol. 32, pp. 87 – 97, 2015. [Online]. Available: http://www.sciencedirect.com/science/article/pii/S0959152415001092

[7] M. A. Brdys, "Intelligent monitoring and control for critical infrastructure systems and application to integrated wastewater treatment systems," in *Large Scale Complex Systems Theory and Applications*, P. Borne and F. G. Filip, Eds., vol. 9, Lille, France, Jul. 2010.

[8] G. Ewald, T. Zubowicz, and M. A. Brdys, "Research platform for monitoring, control and security of critical infrastructure systems," in *Large Scale Complex Systems Theory and Applications*, Y. Xi, Ed., vol. 10, Shanghai, China, Jul. 2013, pp. 278–283.

[9] USEPA, "Epanet 2.0 water network simulation suite," 2001, http://www.epa.gov/nrmrl/wswrd/dw/epanet.html.

[10] F. Shang and L. Rossman, *EPANET Multi-specie extention User's manual*, 2011, ePA/600/S-07/021. National Risk Management Research Laboratory, Natioanl Homeland Security Research Center Office of Research and Developement U.S. Environamental Potection Agency Cincinnati, OH 45268, USA.

[11] L. Rossman, *EPANET 2 User's manual*, Risk Reduction Engineering Laboratory, U.S. Environmental Protection Agency, Cincinnati, OH, 45268, USA, 2000.

[12] W. Findeisen, *Control and coordination in hierarchical systems / W. Findeisen ... [et al.]*. J. Wiley Chichester [Eng.] ; New York, 1980.

[13] L. Monostori, P. Valckenaers, A. Dolgui, H. Panetto, M. Brdys, and B. C. Csáji, "Cooperative control in production and logistics," *Annual Reviews in Control*, vol. 39, pp. 12–29, 2015. [Online]. Available: http://www.sciencedirect.com/science/article/pii/S1367578815000024

[14] M. A. Brdys, "Intelligent monitoring and control for critical infrastructure systems and application to integrated wastewater treatment systems," *IFAC Proceedings Volumes*, vol. 43, pp. 2–12, 2015.

[15] P. Tatjewski, *Advanced Control of Industrial Processes, Structures and Algorithms*. London: Springer Science, 2007.

[16] M. A. Brdys and B. Ulanicki, *Operational Control of Water Systems: Structures, Algorithms and Applications,*. Prentice Hall Int, 1995.

[17] "Matlab documentacion." [Online]. Available: https://www.mathworks.com/help/physmod/simscape/ref/rotationalfriction.html#bqkz82e-6

[18] W. Levine, *The Control Handbook*, ser. Electrical Engineering Handbook. Taylor & Francis, 1996.

[19] Y. Xi, Ed., *13th IFAC Symposium on Large Scale Complex Systems: Theory and Applications*, vol. 10, Shanghai, China, Jul. 2013.