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New tools for teaching vibration damping concepts: ContLab.eu

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Abstract: In last two decades, virtual laboratories help to teach students and train technicians in a broad range of engineering areas including automation and control. However, there is still a lack of laboratories that present more complex control schemes directly related to industrial problems. In this paper, new virtual laboratories presenting feedback and feedforward vibration damping techniques are described. Thanks to the automatic code generation, the presented algorithms are directly deployable to various real-time platforms suitable for teaching/training or professional industrial applications ranging from industrial PCs towards deep embedded boards like *Raspberry Pi*. The interactive tools are freely accessible at www.ContLab.eu. The authors believe that those virtual labs may be useful for both academic and industrial sphere.

Keywords: Vibration damping, input shaping filter, virtual labs, frequency identification, web-based education, automatic code generation, Raspberry Pi

1. INTRODUCTION

In the last two decades, virtual laboratories help to train and teach students and engineers in a broad range of technical areas including automation and robotics (Prieto-Blazquez et al. (2008); Villar-Zafra et al. (2012); Duarte et al. (2008)). They allow making virtual experiments simultaneously by number of clients. Often the remote server is employed to make advanced numerical computations while in other cases the lab is fully self-contained module embedded into webpage. It can be approved that these tools attract more web traffic and help to spread ideas worldwide. Generally, the tools for creating labs are oriented more to process modeling. There is still a lack of laboratories presenting more complex control concepts directly related to industrial problems, in particular to vibration damping. More specifically, the serious drawback of many laboratories is that the built-in algorithm cannot be directly utilized for controlling real plant or machine.

Many virtual labs are powered by the Matlab® engine which computes the state of mathematical model and LabView® software to the display lab GUI (Cheng and Fu (2011); Qiong et al. (2012); Pinto and S da Costa (2013)). In this case, the differential equations are solved on remote Matlab server thus Internet connection is needed to depict simulation results (Koretsky et al. (2008); Uran and Jezernik (2008)). If one wants to get rid of dependence on those large SW platforms, one can use free cross-platform technologies like Java, HTML5+X3D+SVG or flash widgets (Liang and Liu (2013)). For example, Easy Java Simulations (EJS) is often used to develop more self-contained labs which do not need remote server. Unfortunately, the model cannot be built from mature function blocks which is problematic especially when creating complex control scheme (Esquembre (2003); Farias et al. (2010)). Several web function block libraries overcoming this drawback have been developed (e.g. WebConSim reported in Liang and Liu (2013)). Still there is no standard and globally accepted solution available. The modern trends in virtual and remote labs were identified e.g. in Gomes and Bogosyan (2009) and, recently, during the *10-th IFAC Symposium of Advances in Control Education* where the significant shift from virtual/remote to mobile labs was observed (Papadopoulos and Leva (2013)). Roughly speaking, it has two objectives: Firstly, to increase the accessibility of labs through new aids helping to port them to modern platforms like tablets and smart phones. Secondly, to execute the advanced control algorithms at low-cost deep embedded platforms (e.g. Raspberry Pi, Arduino). It brings the opportunity to develop compact portable laboratory models. Additionally, one can see a strong demand for v-labs that easily cooperate with standard platforms and that are fully configurable, thus not hard-coded from scratch. It was also agreed that additional hints like video tutorials increase the teaching attractiveness. Those were main drivers for the work documented below.

This paper follows the authors' previous work Čech et al. (2013) where a new portal ContLab.eu was introduced. It was born on the basis of popular PIDlab web (Schlegel and Čech (2004)), where only the algorithms related to PID control are demonstrated. Nowadays, ContLab covers broader range of automation topics, including vibration damping, motion control and robotics. This paper focuses on new tools for teaching vibration damping concepts.

On ContLab.eu, a novel three-platform paradigm is adopted to create each individual laboratory. The simulation core is

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designed in Matlab/Simulink using RexLib function blocks (Balda et al. (2005)) and then automatically deployed into Java (Čech and Balda (2009)). Similarly, the core can be sent to real-time target for controlling real machine or plant. This ensures that all the three platforms (virtual lab, Matlab/Simulink and real-time target) behave exactly the same way including function block algorithms, parameters and their mutual signal connections. Moreover, the maintenance and update of the core is much simpler compared to traditional way where the major SW part of the lab is coded manually.

This paper describes the ContLab virtual laboratories which are dedicated to feedback and feedforward vibration control and damping in particular. The control techniques are demonstrated on 3D interactive models of gantry crane, spring-mass system and cantilever beam.

The paper is organized as follows: In Section 2, a special technique for automatic generation of simulation cores is described. The features of ContLab laboratories related to vibration damping are explicated in individual subsections of Section 3 where also the teaching goals are summarized. Section 4 shows how easily can be the presented control schemes used for direct control of real plant or machine, two particular applications are mentioned. Conclusions and ideas for future work are given is Section 5.

2. AUTOMATIC CODE GENERATION - THREE PLATFORMS PARADIGM

For development of virtual labs that help to educate/train competitive students/engineers, the following assumptions has been taken into account:

Assumption 1. The highly valuable knowledge is the familiarity with *model based design* and *rapid control prototyping* principles which include: multi-physical component modeling, various simulation levels (MIL, SIL, PIL, HIL) and final implementation on embedded devices, being nowadays identified as the most perspective ICT market [1].

Assumption 2. The virtual labs should become a part of rapid prototyping cycle, therefore the development environment should provide seamless connectivity/portability between various platforms (HW, SW, operating systems).

Having in mind those assumptions, the three platforms idea introduced earlier in Čech et al. (2013) is followed. To ensure that the laboratory algorithms can be extensively tested and simply deployed to real-time targets, particular tools for automatic conversion from simulation and development platform into both real-time target and web virtual laboratory has been developed (see Fig. 1). More specifically, we use the function block library RexLib (Balda et al. (2005)) which is compatible with Matlab/Simulink. In this environment, all the algorithms and advanced control structures can be tested and evaluated. After that, they can be simply deployed to various real-time C-language targets including industrial PCs, PLC/PACs, embedded boards and low cost prototyping platforms like Arduino and Raspberry Pi. The last possibility can be seen as a new evolution step in control education. It is described in Section 4.3 in more details.

[1] Nowadays 95% of microprocessor production is aimed for embedded devices. This assumption is also confirmed by new research directions defined at least in future EU vision Horizon 2020

The essential feature of RexLib library is that the control schemes can be automatically converted also into Java. This technique was developed earlier and is described in Čech and Balda (2009). In such a way, the 100% compatibility of the control schemes at all three platforms is ensured. Consequently, the arisen virtual laboratories are not only "academic" tools but they help to train engineers across the world. They present the control problems in more attractive and interactive way than the pure Matlab/Simulink model.

The laboratories consist of independent SW components with clearly defined interface. For instance, the lab GUI may be implemented in Java or HTML5 and used on tablet/smart phone (fully mobile lab) or on real machine/plant as real-time HMI.

Remark 1. Just imagine how quickly can the engineer get familiar e.g. with the advanced input shaper using the virtual laboratory – even comfortably at home. Thus we believe that the idea of three mutually connected platforms helps to bridge the gap between the academic sphere and industrial practice. Moreover, it fits perfectly into rapid control prototyping *scenario.*

3. VIRTUAL LABS

In this section, the features of two Contlab laboratories related to vibration damping are described. In both labs, it is assumed that the oscillatory process is described as follows:

$$P(s) = \frac{\omega_n^2}{s^2 + 2\xi\omega_n s + \omega_n^2}; \quad \xi < 1,\, \omega_d = \omega_n\sqrt{1-\xi^2}, \quad (1)$$

where ω_n is natural frequency, ξ is damping coefficient and ω_d is damped frequency.

3.1 SC2FA – active feedback vibration damper with autotuner

The SC2FA block implements a state controller for 2$^{\text{nd}}$ order system (1) with frequency autotuner. It is well suited especially for control (active damping) of lightly damped systems ($\xi < 0.1$). But it can be used as an autotuning controller for arbitrary system which can be described with sufficient precision by a transfer function (1). The block has two operating modes: "Identification and design mode" and "Controller mode".

Two points of frequency response with given phase delay are measured during the identification experiment. Based on these two points a model of the controlled system is built. The experiment itself is initiated by the rising edge of the `RUN` input. A harmonic signal with amplitude `uamp`, and frequency ω_n then appears at the block output `mv`. The frequency runs through the interval $\langle\omega_L, \omega_H\rangle$, it increases gradually. The rate at which the frequency changes (sweeping) is determined by the c_p parameter, which defines the relative shrinking of the initial period $T_L = \frac{2\pi}{\omega_L}$ of the exciting sine wave in time T_L, thus

$$c_p = \frac{\omega_L}{\omega_n(T_L)} = \frac{\omega_L}{\omega_L e^{\gamma T_b}} = e^{-\gamma T_L}.$$

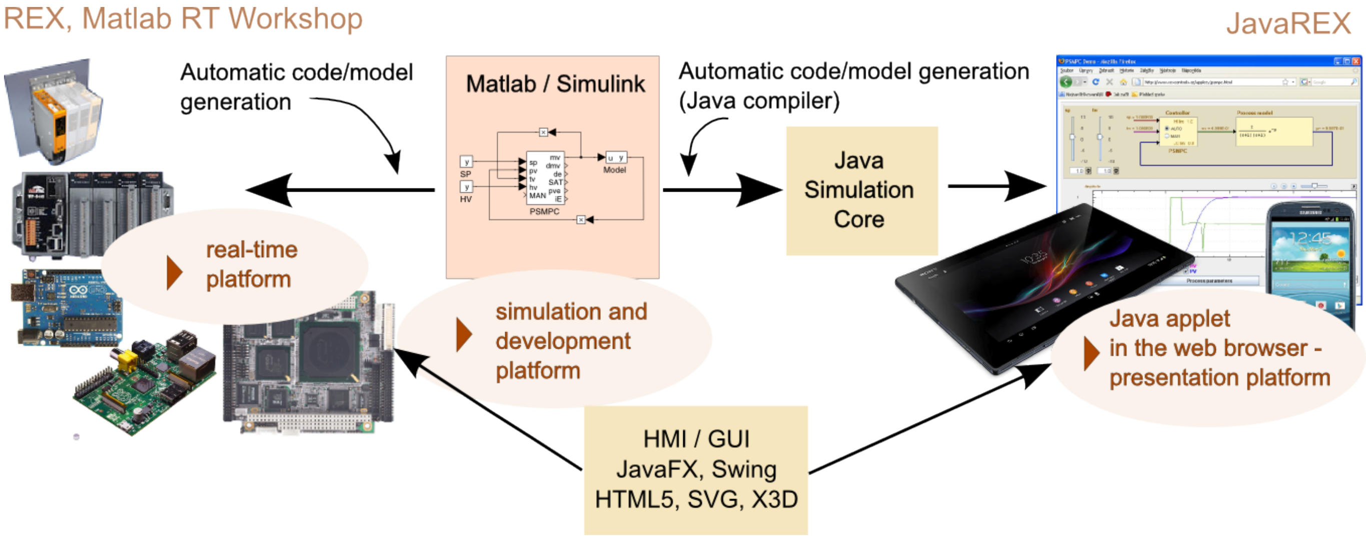

Fig. 1. The three-platforms paradigm: Seamless connection between development, real-time and presentation platforms

The c_p parameter usually lies within the interval $c_p \in \langle 0{,}95; 1)$. The lower the damping coefficient ξ of the controlled system is, the closer to one the c_p parameter must be.

At the beginning of the identification period, the exciting signal has a frequency of $\omega_n = \omega_L$. After a period of `stime` seconds the estimation of current frequency response point starts. The frequency sweeping is stopped two times during the identification period. This happens when points with phase delay of ϕ_1 and ϕ_2 are reached for the first time. Default phase delay values are $\phi_1 = -60°$ and $\phi_2 = -120°$, respectively, but these can be changed to arbitrary values within the interval $(-360°, 0°)$, where $\phi_1 > \phi_2$. Thus we get two points of frequency response with higher precision which are successively used to compute the controlled process model in the form of (1). For the consequential state controller design, the internal model principle and pole placement method are adopted.

A virtual lab has been developed that demonstrates all the block features on a active electromagnetic damping of cantilever beam. The user can start the experiment by one button, check the identification results, and evaluate the active vibration damping performance (Fig. 2).

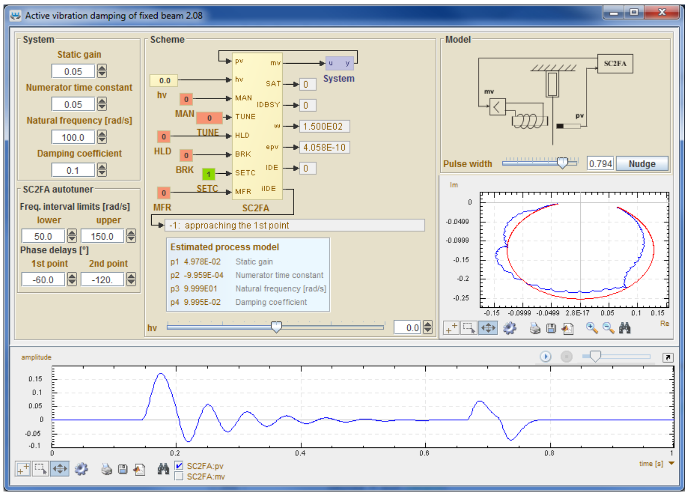

Fig. 2. SC2FA lab GUI – Advanced feedback vibration damping with autotuner

3.2 *ZV4IS – zero vibration input shaper*

Let us consider a second order underdamped system with transfer function (1). Input shaping filter modifies an input signal of this underdamped oscillatory system in order to minimize level of excited oscillations. The input shaper has a structure of weighted sum of time delays, consequently its impulse response is a sequence of n impulses. The filter can be used to solve two fundamental problems: Firstly to control flexible mechanical systems for the purpose of minimization of excited residual vibrations. Second application field is the feedback controller design using open loop frequency response shaping (Schlegel and Goubej (2010)).

Key advantages of this filter are its finite impulse response (FIR), guaranteed stability and monotone step response. In Huey et al. (2008) it is shown that IS filters have shorter delay and better robustness then dynamical notch or low-pass filters. Moreover, the filter is completely parameterized by only two parameters: the natural frequency ω_n and damping ξ of controlled oscillatory mode of the system (1).

One can choose between various filter types depending on knowledge of frequency ω_d. In case this frequency is known exactly, it is suitable to choose a Zero vibration (ZV) filter. This filter adds the smallest possible time delay, but is not very robust. It is recommended to use some of other IS filter types in case of higher uncertainty of system (1) or when noise is present in the loop. The other types are: ZVD (Zero Vibration Derivative), ZVDD, UEI (Extra Insensitive) or UTHEI filters ranging from the least to the most robust, respectively. The ZV4IS block uses four pulse parametrization in form:

$$IS(s) = \sum_{i=1}^{4} A_i e^{-t_i s}; \quad A_i \geq 0, \sum_{i=1}^{4} A_i = 1, \qquad (2)$$
$$0 = t_1 < t_2 < t_3 < t_4,$$

where A_i are amplitudes of particular pulses. ZV4IS comprises all above mentioned types (ZV, ZVD, ZVDD, etc.)

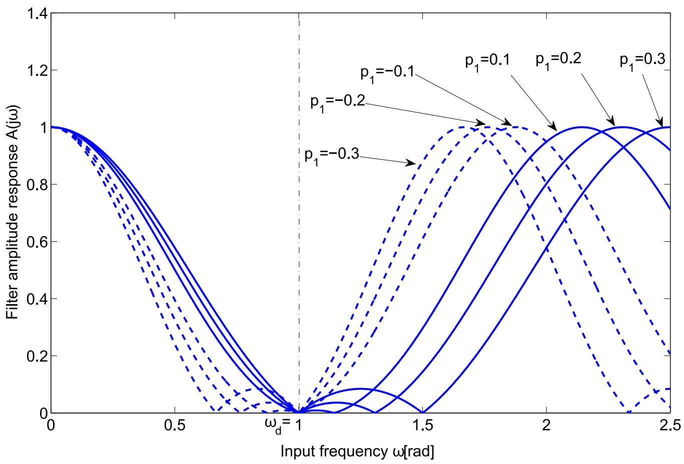

Fig. 3. ZV4IS – Influence of parameter p_1 on the filter amplitude frequency response

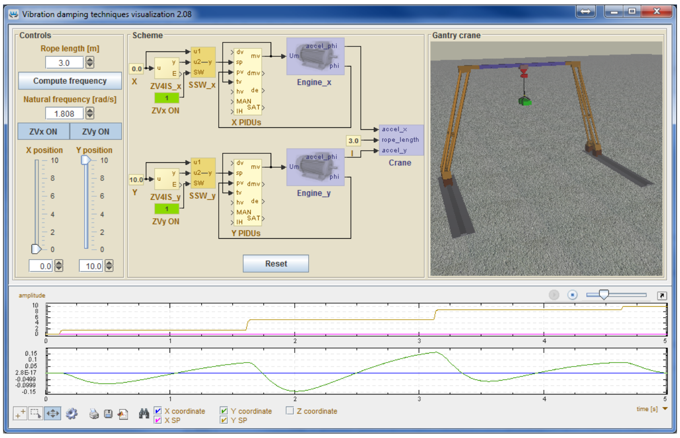

Fig. 4. ZV4IS lab GUI – Input shaping filter demonstrated on 3D gantry crane model

as a special case of general parametrization which is done by three parameters with following ranges:

$$p_1 \in \langle -1, 1\rangle,\ p_2 \in \langle 0, 1\rangle,\ p_3 \in \langle 0, 1\rangle. \tag{3}$$

Each parameter has a clear physical meaning and changes the behavior of the filter in a different way (illustration shown in Fig. 3).

Two simulators have been developed to demonstrate all the features of ZV4IS function block. Firstly, the principle can be evaluated on a gantry crane 3D virtual model (see Fig. 4). The aim is to avoid load oscillations during transport. User can change the rope length, compute model natural frequency and switch the shaping filters for both x and y axis. ZV4IS works as a band stop filter which attenuates the natural frequency. When the filter is switched off, it can be checked how difficult is the manual control of the crane movement.

Secondly, the ZV4IS block can be tested on a 3D model of spring-mass system (Fig. 5). The aim is to avoid oscillations during up/down movement of the load. Similar approach was applied e.g. in stage motion control system.

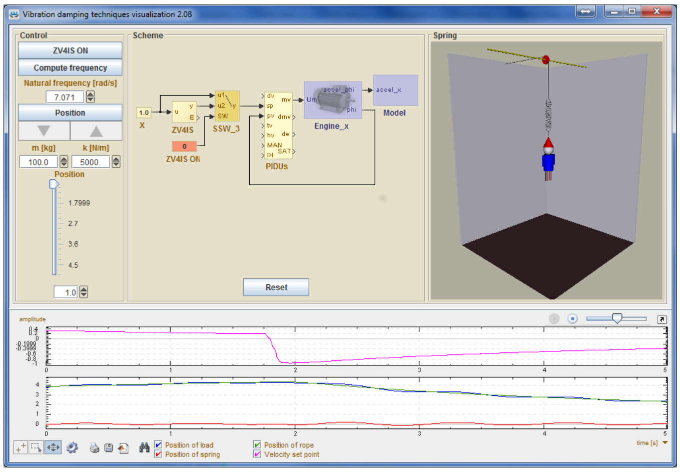

Fig. 5. ZV4IS lab GUI – Input shaping filter demonstrated on 3D spring-mass system model

3.3 Teaching goals

To sum up, the presented labs are freely available to be used for teaching and training especially following topics:

- Internal model principle - active vibration damping
- Pole placement
- Frequency identification
- Input shaping filter parametrization
- Motion control - zero vibration smooth movement

Remark 2. The detailed description of the lab GUI and all function block parameters is available at ContLab.eu. Moreover, the short demo videos have been prepared for each laboratory to attract more students.

4. TARGET PLATFORMS AND APPLICATIONS

The model i.e. simulation core can be automatically deployed to various real-time target. They are summarized in Table 1 together with typical application areas.

In this section, two industrial applications of the algorithms analyzed above are introduced. Thanks to the seamless connection of virtual and real-time platform the students/engineers can firstly get familiar with all the function block features in the virtual lab and then smoothly move to the real plant.

4.1 Aggressive environment robot

Based on the presented ideas, a control system for robotic manipulator AGEBOT (AGressive Environment roBOT) was developed. The manipulator uses special serio-parallel kinematic architecture, which was designed for applications in chemically aggressive environment (Fig. 6). Commonly used industrial robots available on the market cannot be used in such cases because of possibility of destruction or severe damage of vulnerable components of the machine (electronics, sensors and actuators) due to the contact with strong chemicals. The developed manipulator uses special three degrees of freedom parallel spherical wrist, which allows to place all the vulnerable components out of the effector space. The motion of the wrist is realized using a system of linear actuators and cardan joints. The

Table 1. Typical supported real-time target platforms for ContLab.eu algorithms

HW	*Op. system*	*I/O*	*application field / sampling rate*
1. Notebook	Windows XP/7/8	USB modules	mobile laboratory measuring and control system; 500 Hz
2 .Raspberry PI	Raspbian	ARDUIO boards	low cost mobile lab control system; 500 Hz
3. ALIX	GNU RT Linux	Ethernet POWERLINK	control system with remote data acquisition; 1kHz
4. MOXA, LANNER	GNU RT Linux	Eth. POWERLINK/EtherCAT	complex control system with remote DAQ; 1 kHz
5. WinPAC	Windows CE	Plug-in modules	control system with centralized data acquisition; 500 Hz
6. IPC	PharLap ETS	PCI Plug-in cards	high-sample-rate control system; 5 kHz
7. NI HW	NI OS	NI I/O	extra high-sample-rate control system, FPGA; >5 kHz
8. d-Space	d-Space	d-Space I/O	complex measurement and HIL simulations; >10 kHz

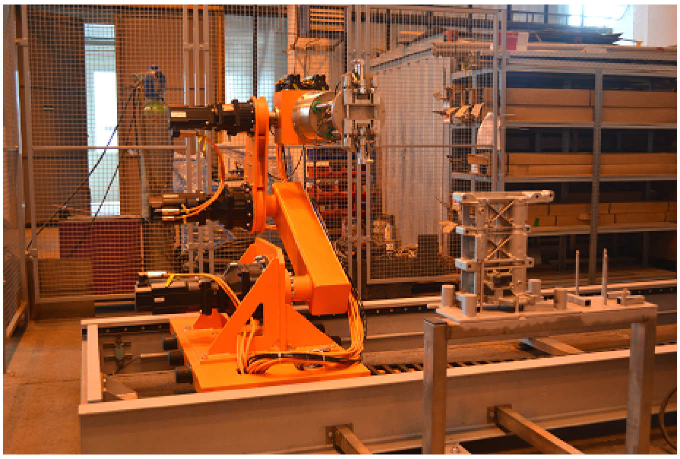

Fig. 6. ZV4IS application – smooth motion of advanced robot

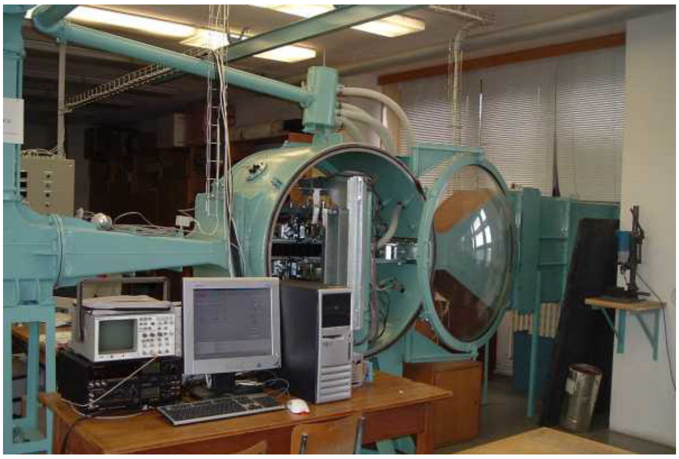

Fig. 7. SC2FA application – active damping of vibrating vanes in the wind tunnel

developed manipulator is equipped with automatic computer control system which allows to define and parameterize desired motions and human-machine interface for supervision and control by a human operator. The ZV4IS function block is an inseparable part of this control system that helps reduce the vibrations which are normally excited in the mechanical robot arm during fast motion. The system runs on embedded PC with 1kHz sampling rate (see line 4 in Tab. 1). The primary application for the robot is technology of industrial degreasing and paint removing which is supplied by company EuroTec JKR. However, it is possible to adapt the robot easily for different tasks thanks to universal communication interface which allows a connection to arbitrary supervisory technological control system using standard communication protocol.

4.2 Active damping of vibrating vanes in the wind tunnel

The task of the active vibration damping of vanes in the wind tunnel was proposed to explore a relative motion of the turbine vanes (Fig. 7). The system in the wind tunnel contains active and stationary vanes. The active vanes have their natural frequency approximately $\omega_n = 84$ Hz and the damping ratio $\xi = 0.015$. Therefore the control system and the identification process must satisfy the high-speed requirements. The system of active vibration damping belongs to the class of oscillatory processes. Hence one can benefit from use of SC2FA controller with autotuning function, because of many experiments with different configurations of the whole system. Note, that it is necessary to re-tune the controllers after each modification of the vanes system. The autotuning controller is based on the frequency identification, the internal model principle and the state feedback control. Two industrial PCs with the operating system PharLap ETS were used to control these oscillating vanes with 5kHz sampling rate (see line 6 in Tab. 1).

4.3 Deployment of ContLab algorithms to Raspberry Pi + Arduino

Among professional apps, all ContLab algorithms may be run at Raspberry Pi using Arduino as input/output device (see line 2 in Tab. 1). The mentioned microcomputers, which the platform is based on, form a perfect couple for control education, combining the computational power [2], onboard memory and Ethernet connectivity of the Raspberry Pi and relatively rich input-output capabilities of the Arduino board. The basic structure of such system is shown in Fig. 8, the details are omitted for brevity and can be found in Sobota et al. (2013).

5. CONCLUSION

In this paper, new tools for teaching/training active vibration damping were documented. Both feedback and feedforward techniques were discussed. A special procedure for automatic generation of laboratory simulation core was recapped. The possibility to deploy the presented advanced algorithms to various target platforms was accented. From teaching perspective, porting to the deep embedded platforms like Raspberry Pi is the most valuable. Finally, several professional applications of presented vibration techniques were mentioned. The virtual

[2] Lets admit that this platform can be used for active vibration damping only for $\omega_n \leq 50Hz$

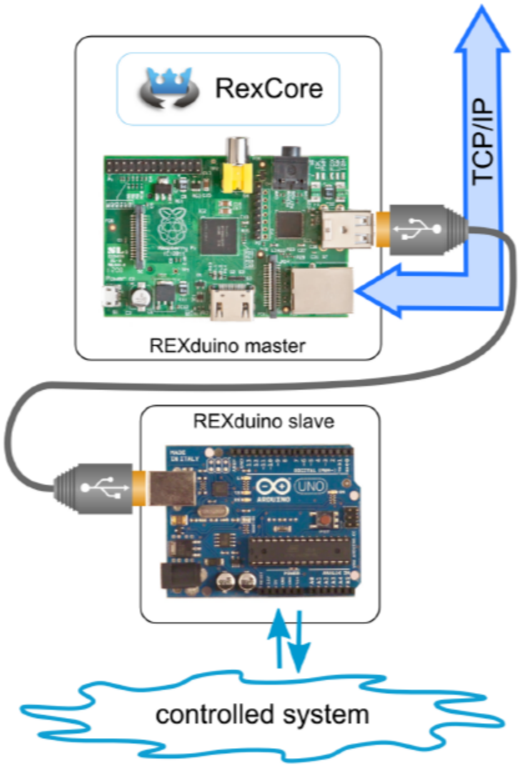

Fig. 8. Raspberry Pi + Arduino – the extremely low cost platform for running ContLab.eu algorithms in real-time

simulators reduced significantly the time of training the operators working with those machines/stands. The future R&D will focus at the virtual presentation of vibration damping in the whole motion control chain, in cooperation with PLCopen Motion Control library.

REFERENCES

Balda, P., Schlegel, M., and Štětina, M. (2005). Advanced control algorithms + Simulink compatibility + real-time OS = REX. In *Proceedings of IFAC 2005*, volume 16, 2292–2292. Praque, Czech Republic.

Cheng, Q. and Fu, B. (2011). Research and implement of the virtual laboratory of power electronics based on LabVIEW. In *Computer Science Education (ICCSE), 2011 6th International Conference on*, 619 –622. doi: 10.1109/ICCSE.2011.6028715.

Duarte, M., Butz, B., Miller, S., and Mahalingam, A. (2008). An Intelligent Universal Virtual Laboratory (UVL). *Education, IEEE Transactions on*, 51(1), 2 – 9. doi:10.1109/TE.2006.888902.

Esquembre, F. (2003). Using Easy Java Simulations to create scientific simulations in Java. In *EUROCON 2003. Computer as a Tool. The IEEE Region 8*, volume 1, 20 – 23 vol.1. doi:10.1109/EURCON.2003.1247971.

Farias, G., De Keyser, R., Dormido, S., and Esquembre, F. (2010). Developing networked control labs: A Matlab and Easy Java Simulations approach. *Industrial Electronics, IEEE Transactions on*, 57(10), 3266 –3275. doi: 10.1109/TIE.2010.2041130.

Gomes, L. and Bogosyan, S. (2009). Current trends in remote laboratories. *Industrial Electronics, IEEE Transactions on*, 56(12), 4744–4756. doi: 10.1109/TIE.2009.2033293.

Huey, J.R., Sorensen, K.L., and Singhose, W.E. (2008). Useful applications of closed-loop signal shaping controllers. *Control Engineering Practice*, 16(7), 836 – 846. doi:10.1016/j.conengprac.2007.09.004.

Koretsky, M., Amatore, D., Barnes, C., and Kimura, S. (2008). Enhancement of student learning in experimental design using a virtual laboratory. *Education, IEEE Transactions on*, 51(1), 76 –85. doi: 10.1109/TE.2007.906894.

Liang, Y. and Liu, G.P. (2013). Design of remote 3d virtual laboratory for education on control system experimentation. In *Proceedings of 10th IFAC Symposium of Advances in Control Education*, 227–231. Sheffield (UK).

Papadopoulos, A. and Leva, A. (2013). Laboratories over the network: from remote to mobile. In *Proceedings of 10th IFAC Symposium of Advances in Control Education*, 84–88. Sheffield (UK).

Pinto, J.C. and S da Costa, J. (2013). Virtual and remote laboratories for industrial automation e-learning. In *Proceedings of 10th IFAC Symposium of Advances in Control Education*, 286–290. Sheffield (UK).

Prieto-Blazquez, J., Arnedo-Moreno, J., and Herrera-Joancomarti, J. (2008). An integrated structure for a virtual networking laboratory. *Industrial Electronics, IEEE Transactions on*, 55(6), 2334 –2342. doi: 10.1109/TIE.2008.921231.

Qiong, C., Zhilin, D., and Li, L. (2012). Implementation of virtual laboratory of power electronics based on matlab and labview. In *Computer Science Education (ICCSE), 2012 7th International Conference on*, 1539 –1544. doi: 10.1109/ICCSE.2012.6295356.

Schlegel, M. and Goubej, M. (2010). Feature-based parametrization of input shaping filters with time delays. In *IFAC Proceedings Volumes (IFAC-PapersOnline)*, 247–252.

Schlegel, M. and Čech, M. (2004). Internet PID controller design: www.PIDlab.com. In *Proceedings of IBCE 04*, 1–6. Grenoble, France.

Sobota, J., Pišl, R., Balda, P., and Schlegel, M. (2013). Raspberry Pi and Arduino boards in control education. In *Proceedings of 10th IFAC Symposium of Advances in Control Education*, 7–12. Sheffield (UK).

Uran, S. and Jezernik, K. (2008). Virtual laboratory for creative control design experiments. *Education, IEEE Transactions on*, 51(1), 69 –75.

Čech, M. and Balda, P. (2009). A New Technique for Automatic Generation of Java Applets for Web-based Control Education. In M. Fikar and M. Kvasnica (eds.), *Proceedings of the 17th International Conference on Process Control '09*, 491–497. Slovak University of Technology in Bratislava, Štrbské Pleso, Slovakia.

Čech, M., Schlegel, M., Balda, P., and Severa, O. (2013). A new extensive source for web-based control education Contlab.eu. In *Proceedings of 10th IFAC Symposium of Advances in Control Education*, 1–6. Sheffield (UK).

Villar-Zafra, A., Zarza-Sanchez, S., Lazaro-Villa, J., and Fernandez-Canti, R. (2012). Multiplatform virtual laboratory for engineering education. In *Remote Engineering and Virtual Instrumentation (REV), 2012 9th International Conference on*, 1 –6.