Socio cyber-physical system with piezoactuator

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Abstract. The article describes a cyber-physical system, on ACV Educational Kit with the APA-60SM piezo actuator and STM32F4Discovery module from STMicroelectronics from the physical world to the cybernetic world using the MATLAB program and works in a social environment via the Internet. The questions of prototyping digital control systems for piezo-actuator systems using MATLAB Simulink are considered. It is experimentally shown that system allows automating the control object dynamic characteristics research and developing control algorithms for piezo actuators in real time on field samples. At the current stage, remote addition of applications by users and the ability to process applications by the system administrator are implemented.

1. Introduction
Cyber-physical systems combine digital and analog devices, interfaces, networks, computer systems, and the like with the natural and man-made physical world [1].

The integration of the Cyber-physical system into the social environment allows talking about Socio Cyber-physical systems.

The device described in the article [13] is an example of a Cyber-physical system, since it integrates a device from the physical world (ACV Educational Kit) into the cybernetic world (MATLAB program).

The development of automatic control systems for piezo actuators is usually difficult due to parameters spread of both the actuator and the control object [5]. At the same time, many design system issues would be successfully solved using real-time systems rapid prototyping technology using modern computer systems [6]. This technology is actively supported and promoted by many leading developers of specialized software. Among them MATLAB software from MatWork and LabView from National Instruments [7, 12] are especially notable. This article discusses the organization of prototyping digital control systems for piezo actuators using MATLAB Simulink and the specialized Wajung Blockset library for working with the STM32F407 microcontroller [4].

2. Hardware-software system
2.1. Mechanical part
The mechanical part was built on Educational Kit ACV (Active control of Vibrations) from Cedrat Technologies (France) [3] and shown in Figure 1. The system contains a thin-film stacked amplified piezo actuator APA-60SM, numbered 1 on Figure 1 with integrated mechanical lever for micro-motion multiplier. The piezoactuator is mounted on a rigid massive base 2 and connected by a rigid rod with a
flexible rod 3. The rod parameters movement are measured by an analog accelerometer 4 and an optical displacement sensor 5. An electromagnet 6, powered by a power amplifier 7, allows applying a controlled disturbance to the rod 3. A voltage and current on piezoactuator control circuit are measured. A piezoelectric actuator mounted on a bench is capable to provide 80 microns stroke. The connection of the piezoelectric actuator with a 330 mm rigid rod allows increasing the created motion up to 500 microns, depending on the selected measuring point of movement along the flexible rod.

![Figure 1. Educational Active control of Vibration, ACV Kit.](image)

2.2. ACV Educational Kit communication with a computer
To connect the ACV Kit with a computer, convert signals from analog form to digital and vice versa, the STM32F4Discovery module from STMicroelectronics is used. The module built on the basis of the 32-bit STM32F407 microcontroller containing all the elements necessary for control: 12-bit ADCs and DACs, pulse-width converters, transceiver blocks, timers, etc. The STM32F4Discovery module is used as an intelligent input-output device for regulator prototyped control system.

The piezoactuator control signal would be generated either by microcontroller digital-to-analog or pulse-width converters. The control signal for piezoactuator is amplified by a high-voltage amplifier with a gain of 45 to obtain the piezoactuator operating voltage in the range 0 ... 150 V. The control signal of the electromagnet is also generated either by digital-to-analog or pulse-width converters and amplified by a power amplifier.

Operational preparation and implementation of the software part of the control system is carried out by MATLAB Simulink using a specialized software Waijung Blockset library modules for the STM32F407 microcontroller, [8]. The investigated control system regulator, as well as disturbance generator, is created by Simulink tools. Further, using Waijung Blockset library tools, code is generated and loaded into the microcontroller module. In addition, real-time communication between the microcontroller module and Simulink were confirmed to implement master control changes and display task trial runs results.

Thus, the complex for prototyping digital control systems allows implementing Hardware-In-the-Loop, so-called HIL mode, i.e. provides closed-loop control of a physical system in real time. It has been experimentally confirmed that on a medium-power computer running Win7 OS, the system operates with 0.0002 s sampling time. Such a short sampling time allows controlling systems
prototyping with sufficiently fast controllers, including relay controllers with a zero-overshoot response or maximum speed modes of operation.

Figure 2. Functional diagram of software-hardware system part.

2.3. Test signals generation
A typical problem that occurs when digital control systems prototyping in HIL mode is related to the computer operating system used. Thus Windows is a multi-tasking system and does not allow running a priority task that works in real time with a sampling time less than 50 ms. An attempt to implement such control systems leads to instability of the sampling time and, as a result, to incorrect prototyping results. To fix such issue, software developers apply various solutions - from creating special real-time operating systems to developing special tools for automatically generating a control program that runs outside the computer’s operating system, [9]. In the second case, the prototype control system controller is implemented by an external slave controller and the problem of sampling time instability fixed. It remains only to ensure the stability of the master effect, which is usually formed by the host computer.

Figure 3. System response for step (a) and sinusoidal (b) signals.
There are step and harmonic signals which can be considered as typical driving signals for control systems, for the formation of which there are blocks in Simulink. Forming quality of driving signal it is easy to verify it. For that 1 clock signal delay and return the delayed signal to host computer for visualization program would be loaded in the STM32F4Discovery module. Figure 3 shows the response signals received from the STM32F4Discovery module of the described complex, corresponding to step (a) and sinusoidal signals with 16 Hertz frequency (b) for a 0.001 second sampling time. In Figure 3 it can be seen that the effects in the initial section have a time delay of the 0.05 second order. In addition, the harmonic signal in the initial section has significant shape distortion.

Initial delays and waveform distortion are caused by the MATLAB and Waijung Blockset software products features that can not be eliminated by the user. Therefore, it is advisable to include additional blocks in the structure of the prototype controller that make it possible to cut off the reception of the setting action at the initial section of the program. For this purpose, an additional step signal can be used, supplied from the Simulink software environment to the STM32F4Discovery module, delayed for a fixed time relative to the main signal. This additional signal is used to enable the controller.

2.4. Control object model parameters identification
Unlike a conventional piezo actuator, the APA-60SM piezo actuator used in the ACV Kit has a mechanical lever for micro-movement multiplier. Due to this mechanical design, the APA stroke increases by several times. However, there is a drawback - the rigidity of the structure is noticeably reduced. As a result, the movement of the control object in time has considerably oscillatory form. The control object main resonance frequency is about 24 Hertz.

Using the System Identification Toolbox from the MatLab Simulink library, [10], in the semi-automatic mode, the mathematical model parameters of control object were evaluated with the exit by displacement. Identification was carried out by the control object transient response. Fig. 4 shows control object static characteristic (a) and control object typical reaction to the step function (b).

![Figure 4. System static characteristic (a) and reaction on step function (b).](image-url)
where: \( y(t) \) is the displacement of the piezoelectric actuator rod (mm); \( l(t) \) is the measured displacement of the control object (mm); \( U_p(t) \) - control signal (V); \( K_1 = 118.4 \text{ mm} / \text{V}s^2 \), \( K_2 = 1.91 \times 10^6 \text{ l/s}^2 \), \( a_0 = 6.34 \times 10^4 \text{ l/s}^2 \), \( a_1 = 531 \text{ l/s} \), \( b_0 = 2.52 \times 10^4 \text{ l/s}^2 \), \( b_1 = 3.82 \text{ l/s} \).

\[
\ddot{y}(t) + a_1 \dot{y}(t) + a_0 y(t) = K_1 U_p(t),
\]

\[
\Delta \ddot{l}(t) + b_1 \Delta \dot{l}(t) + b_0 \Delta l(t) = K_2 y(t),
\]

Coincidence with the reaction of the control object in Figure 4(b) was 82%.

Model similar to [2] were used to describe the APA120 piezoactuator hysteresis loop. A non-linear equation for the description of hysteresis is added to equations (1). The final nonlinear model of the control object has the form:

\[
\ddot{y}(t) + a_1 \dot{y}(t) + a_0 y(t) = K_1 U_p(t),
\]

\[
\dot{h}(t) = a_0 \dot{y}(t) - b_1 l(t) \dot{h}(t) - \gamma \dot{y}(t) h(t),
\]

\[
\Delta \ddot{h}(t) + b_1 \Delta \dot{h}(t) + b_0 \Delta h(t) = K_2 [y(t) - h(t)],
\]

where: \( h(t) \) is the output of the nonlinear block (mm) \( \alpha = 0.0801 \), \( \beta = 0.0152 \text{ 1/mm} \), \( \gamma = -0.0227 \text{ 1/mm} \). Coincidence with the reaction of the control object Fig. 4b was 86%.

2.5. Prototyping the digital analog of the PI controller

For prototyping regulators experiments, a PI digital analogue regulator was chosen.

![Figure 5. System reaction on step function of a control system with a digital controller configured according to a linear model (a) and similar reaction obtained by simulation in Simulink (b).](image-url)
For automatic adjustment of such regulator, Simulink has a special module - the Control Toolbox. It is possible to perform a functional test of Simulink services in conjunction with the Wajung Blockset library in research automation tasks.

The automatic adjustment of the PI controller to work with the control object defined by linear equation (1) yielded the following parameters: transmission coefficient of the proportional component $K_p = 0.01 \text{ V/mm}$, transmission coefficient of the integral component $K_i = 20 \text{ V/s*mm}$. The application of the PI controller tuning procedure for working with a nonlinear model of the control object determined the following controller parameters: $K_p = 0.1 \text{ V/mm}$, $K_i = 25 \text{ V/s*mm}$.

Figure 5a shows a comparison of the reaction (curve 1) on the step function of a control system with a digital controller configured according to a linear model with a similar reaction (curve 2) obtained by simulation in Simulink. Figure 5b shows similar reactions of control systems with a controller tuned according to a nonlinear model. The sampling period in both cases is 0.002 s.

The control system model and its full-scale prototype reaction comparison showed fine coincidence between the results. This allows concluding that the use of the Wajung Blockset library allows quick use of the basic Simulink services for the analysis, identification and synthesis of digital controllers of full-scale object control systems with thin-film piezo actuators. Distortions in the formation of master actions do not significantly affect the results and can be eliminated by software.

3. Connecting a cyber-physical system to a social network

In order for the device to be used by scientists from all over the world it must be connected to the social environment. Such an environment is the Internet.

To organize communication, we need a system that allows building interaction with all elements of Socio Cyber-physical system - web application [14]. The structure of this web application is presented in the Fig. 6.

The web application (“Social Core” in the figure) automates the process of remote use of laboratory equipment. The equipment interacts with the MATLAB program located on the computer (“Cyber-system” in Fig. 6).

To get started, the user needs to register an account in the service. After that, the user submits an order for the experiment: generates an experiment file in the MATLAB program on computer and attaches this file to the order. The order consists of a description and an experiment file. There is a laboratory administrator in the service, after the user has added the order the administrator downloads the experiment file, loads his Cyber-physical system into the MATLAB program and starts the experiment on the equipment. After the experiment the administrator uploads the experiment result to the order, changes the order status to “Completed” and saves the order. After that, the user can download the result file and open it on his computer in the MATLAB program and analyze the obtained data.

![Figure 6. Structure of the service socialcps.ru.](image)
4. Conclusion
At the current stage, remote order addition by users and the ability to process orders by the system administrator are implemented. It is planned to automate the process of reading orders and processing them through the Cyber-system in order. The hardware-software complex for prototyping piezoelectric actuators digital control systems allows automating control object dynamic characteristics research and developing control algorithms in real time on field samples. In addition, the absence of the need for laborious development of program code for the synthesized controller makes it possible to use the complex for educational purposes.

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References
[1] Sanfelice R G 2015 Analysis and Design of Cyber-Physical Systems: A Hybrid Control Systems Approach In Cyber Physical Systems: From Theory to Practice (CRC Press) pp 3–31
[2] Royson D D’Souza, Benny B, Sequeira A and Karanth P N 2016 Hysteresis modeling of amplified piezoelectric stack actuator for the control of the microgripper American Scientific Research Journal for Engineering, Technology, and Sciences
[3] Active Structure Control 2019 On Cedrat Technologies Website, available at: https://www.cedrat-technologies.com/en/products/actuators/amplified-piezo-actuators.html
[4] Torgaev S N, Trigub I S and Musorov D S 2015 A practical guide to programming STM – microcontrollers (Tomsk Polytechnic University)
[5] Bobtsov A A 2011 Actuators and Systems for Microdisplacement (St Petersburg: ITMO)
[6] Dickens M 2019 Accelerated prototyping and semi-natural modelling, available at: http://controlengrussia.com/programmye-sredstva/uskorennoe-prototipirovanie-i-polunaturnoe-modelirov/
[7] Anufriev I E, Smirnov A B and Smirnova E N 2005 MATLAB 7 (St. Petersburg: BHV-Petersburg)
[8] Nguyen V K 2016 A framework for transferring algorithms designed on MATLAB / SIMULINK to ARM microcontroller embedded systems Can Tho University Journal of Science 4 36–45
[9] Smolentsev N K 2008 Creation of Windows applications using mathematical procedures MATLAB (Moscow: DMK Press)
[10] Chernykh I V 2008 Modeling of electrical devices in MATLAB, SimPower Systems and Simulink (Moscow: DMK Press)
[11] Boykov V I, Bystrov S V, Grigoryev V V and Obertov D E 2009 Piezodrive based on thin-film piezoelectric actuators Bulletin of higher educational institutions. Instrument making 52(11) 84–88
[12] Travis J 2005 LabVIEW for All trans. by Klushin N A (Moscow: DMK Press)
[13] Boykov V I, Bystrov S V, Karev P V, Kulchitsky A A, Nguyễn B H and Smirnov A Y 2019 Prototyping digital control system packet piezoactuators means MATLAB, in press.
[14] Web-interface Socialcps 2019 Available at: https://socialcps.ru.