Electrohydraulic Servo Actuators with IoT Capabilities

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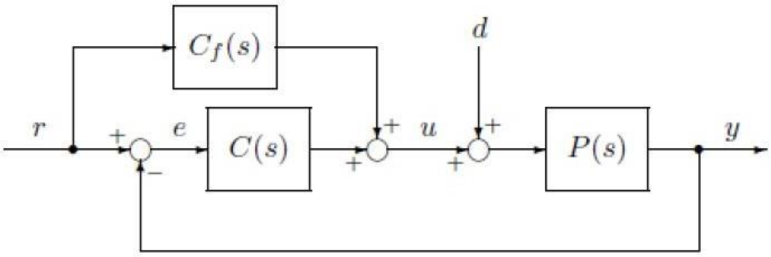
Abstract: *The following document details an electrohydraulic servo actuator system with Internet of Things (IoT) functionalities, highlighting its main components: control electronics, the servo amplifier, the power supply, the servo valve, the hydraulic actuator, and the feedback transducer. The system utilizes a two-degree-of-freedom (2- DOF) controller and IoT integration for monitoring and preventive maintenance. The system implementation is done using a Modicon M221 PLC and a Raspberry Pi single-board computer for the local server and monitoring. The conclusions emphasize the improvement of remote monitoring and system parameterization, suggesting future research directions for the development of cloud-based business models.*

Keywords: *Electrohydraulic actuator, IoT integration, 2-DOF controller, remote monitoring, PLC*

1. Preliminaries

An electrohydraulic actuator system comprises six key components: control electronics, which can be a computer, microprocessor, or guidance system, creating a command input signal; a servo-amplifier that provides a low-power electrical actuating signal, which is the difference between the command input signal and the feedback signal generated by the feedback transducer; a power supply, typically an electric motor and pump, delivering hydraulic fluid flow under high pressure; a servo valve that responds to the low-power electrical signal and regulates the hydraulic fluid flow to an actuation element, such as a piston and cylinder, positioning the controlled device; a hydraulic actuator, consisting of a piston and cylinder, to control linear motion and positioning; and a feedback transducer that measures the actuator's output position and converts this measurement into a proportional signal sent back to the servo-amplifier [1]. A general form of the 2-DOF control system is shown in fig.1 [2]. The key components of this system include the feedforward compensator $C_f(s)$, the serial compensator C(s) and plant process P(s). The set-point variable r represents the desired target, while the manipulated variable u is the output from the compensators that adjusts the plant. The controlled variable y is the output of the plant, which is affected by external disturbances d. Error e is the subtraction of y from r.



$$C(s) = K_P\left\{1+\frac{1}{T_I s}+T_D D(s)\right\}$$

$$C_f(s) = -K_P\{\alpha+\beta T_D D(s)\}$$

Fig. 1. Two-degree-of-freedom control system

In this configuration, the feedforward compensator $C_f(s)$ directly processes the set-point variable r to anticipate and mitigate disturbances before they affect the plant. The serial compensator C(s) is part of the feedback loop, working to continuously correct deviations between the controlled variable y and the set-point variable r.

Hydraulic drives typically utilize two types of actuators: position-controlled linear actuators and speed- controlled rotary actuators. For position-controlled linear actuators, the feedforward path command is derived from the reference point's derivative, so α = 0. In contrast, speed-controlled rotary actuators require a feedforward path command that is directly proportional to the set-point value, thus ß = 0 for effective control [3].

A single-board computer (SBC) is a fully functional computer where the microprocessor, input/output functions, memory, and other features are integrated onto a single circuit board. It includes a fixed amount of built-in RAM and lacks expansion slots for peripherals. This straightforward design contrasts with the multiple configurations available in modern personal computers, yet its simplicity ensures reliability, making these ideal as embedded computer controllers for operating complex devices.

2. Controller implementation

The controller command is as follows:

$$u(s) = K_p \cdot err(s) \cdot \left[1 + T_d \cdot s + \frac{1}{T_i \cdot s}\right] + K_f \cdot [\alpha \cdot s \cdot sp(s) + \beta \cdot sp(s)] \tag{1}$$

The FF compensator is calibrated depending on the physical parameter that the transducer’s output value is proportional to (either proportional to the set-point (α = 0, ß <> 0), its derivative (α <> 0, ß = 0) or both (α <> 0, ß <> 0)).

The 2-DOF PID control algorithm was implemented using the Modicon M221 entry-level PLC [4]. The software development platform for this PLC is EcoStruxure Machine Expert-Basic, a free licensed programming software specifically designed for M221 controllers. Modicon offers performance and scalability suitable for a wide range of industrial applications, from entry-level tasks to high-performance multi-axis machines and high-availability redundant processes.

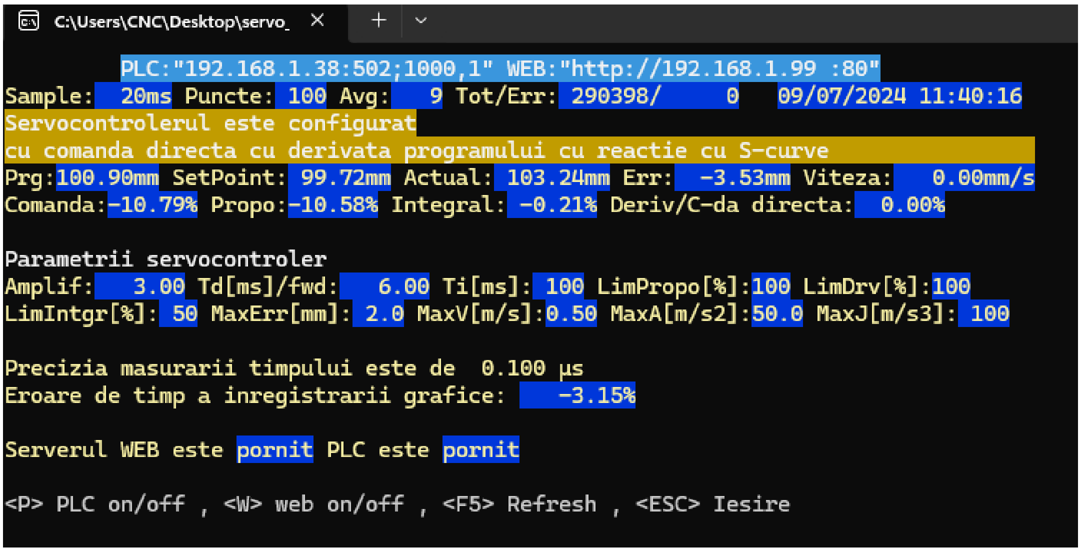
Regarding hardware implementation, a TM221CE24T controller was used, with 14 digital inputs, 2 analogue inputs, Ethernet and serial line ports, with 24 Vdc power supply. To interface the actuator with the PLC, a TM3AM6 analogue expansion module is required. The TM3AM6 module has 4 analogue inputs (±10 V, 0-10 V, 0-20 mA, 4-20 mA), 2 analogue outputs (±10 V, 0-10 V, 0-20 mA, 4-20 mA) and a 12-bit resolution.

A Raspberry Pi RPI4-MODBP 8GB [5] was used as the remote computer for a localhost server used for monitoring and parametrization of the controller, as part of the IoT system. The Raspberry Pi 4 Model B (RPI4-MODBP) with 8GB RAM is a versatile single-board computer, featuring 40-pin GPIO header, providing 26 GPIO pins that can be used as digital inputs or outputs, with support for I2C, SPI, and UART communication protocols, as well as a Gigabit Ethernet port.

3. IoT implementation for monitoring and parametrization

For monitoring and parametrization of the controller, a Pascal-based program was developed, using Lazarus IDE [6], that runs on a SBC in the same network as the controller. The application server runs in a terminal window (**fig. 2**) that features management of the current state of the IoT system (PLC on/off, web server on/off) and details about control system variables and controller parameters.

With this app open, a localhost web page can then be accessed to further monitor the system.



```
         PLC:"192.168.1.38:502;1000,1" WEB:"http://192.168.1.99 :80"
Sample:  20ms Puncte: 100 Avg:    9 Tot/Err: 290398/     0   09/07/2024 11:40:16
Servocontrolerul este configurat
cu comanda directa cu derivata programului cu reactie cu S-curve
Prg:100.90mm SetPoint: 99.72mm Actual: 103.24mm Err:  -3.53mm Viteza:   0.00mm/s
Comanda:-10.79% Propo:-10.58% Integral: -0.21% Deriv/C-da directa:  0.00%

Parametrii servocontroler
Amplif:   3.00 Td[ms]/fwd:   6.00 Ti[ms]: 100 LimPropo[%]:100 LimDrv[%]:100
LimIntgr[%]: 50 MaxErr[mm]: 2.0 MaxV[m/s]:0.50 MaxA[m/s2]:50.0 MaxJ[m/s3]: 100

Precizia masurarii timpului este de  0.100 µs
Eroare de timp a inregistrarii grafice:    -3.15%

Serverul WEB este pornit PLC este pornit

<P> PLC on/off , <W> web on/off , <F5> Refresh , <ESC> Iesire
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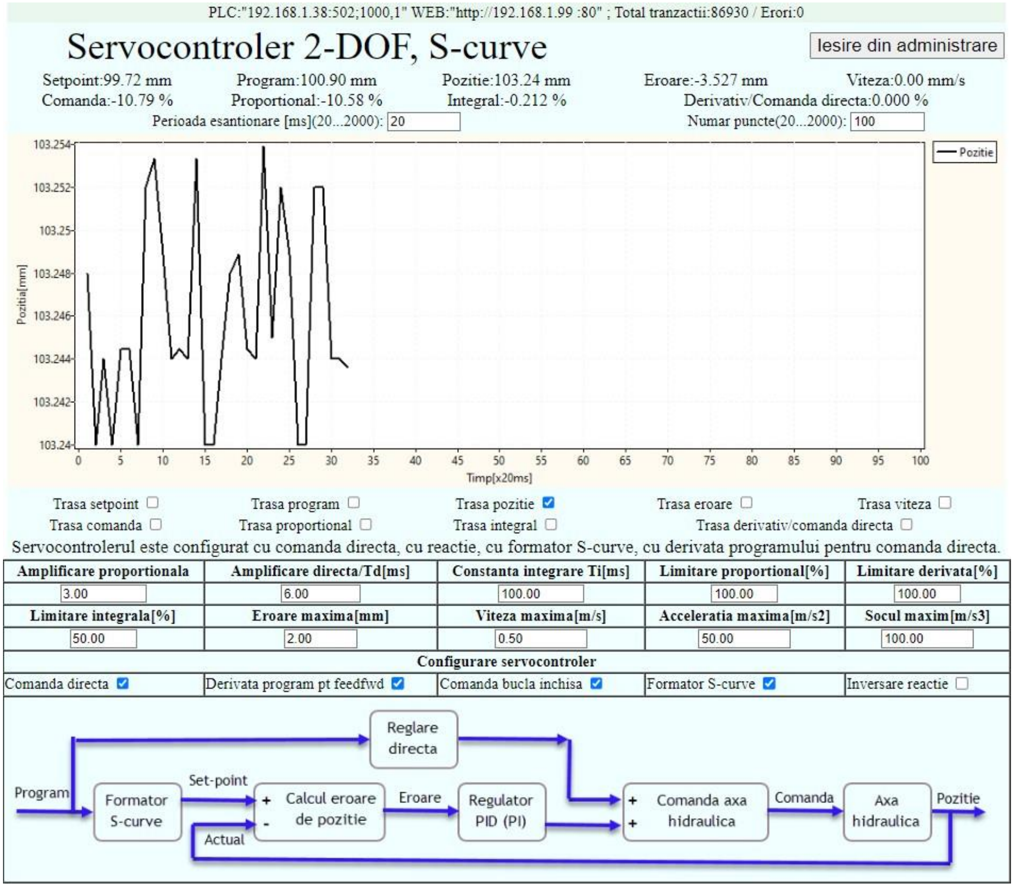
Fig. 2. Server's terminal window

Inside this webpage, a user can either access a read-only window of the evolution of different measured values or access an administrator panel using a login feature. The administrator window, as shown in **fig. 3**, allows for variation of the 2-DOF controller parameters and configuration of the output graph, for showing multiple variables in the time frame.

The values are set via the controller's Ethernet interface using the MODBUS over TCP/IP protocol. MODBUS is a widely used communication protocol in industrial automation and is supported by many devices and controllers. Furthermore, implementing MODBUS over TCP/IP can be cost-effective compared to proprietary protocols or more complex communication standards. It leverages existing Ethernet infrastructure without requiring significant additional investment.



PLC:"192.168.1.38:502;1000,1" WEB:"http://192.168.1.99 :80" ; Total tranzactii:86930 / Erori:0

Servocontroler 2-DOF, S-curve

Setpoint:99.72 mm Program:100.90 mm Pozitie:103.24 mm Eroare:-3.527 mm Viteza:0.00 mm/s
Comanda:-10.79 % Proportional:-10.58 % Integral:-0.212 % Derivativ/Comanda directa:0.000 %
Perioada esantionare [ms](20...2000): 20 Numar puncte(20...2000): 100

Trasa setpoint ☐ Trasa program ☐ Trasa pozitie ☑ Trasa eroare ☐ Trasa viteza ☐
Trasa comanda ☐ Trasa proportional ☐ Trasa integral ☐ Trasa derivativ/comanda directa ☐

Servocontrolerul este configurat cu comanda directa, cu reactie, cu formator S-curve, cu derivata programului pentru comanda directa.

Amplificare proportionala	Amplificare directa/Td[ms]	Constanta integrare Ti[ms]	Limitare proportional[%]	Limitare derivata[%]
3.00	6.00	100.00	100.00	100.00
Limitare integrala[%]	**Eroare maxima[mm]**	**Viteza maxima[m/s]**	**Acceleratia maxima[m/s2]**	**Socul maxim[m/s3]**
50.00	2.00	0.50	50.00	100.00
Configurare servocontroler				
Comanda directa ☑	Derivata program pt feedfwd ☑	Comanda bucla inchisa ☑	Formator S-curve ☑	Inversare reactie ☐

Fig. 3. Client browser window for the administrator

Fig. 4 shows the block diagram of the automated system for controlling a hydraulic actuator using a position transducer, PLC, and a single board computer [7]. The PLC receives input from the position transducer and controls the hydraulic system. The single board computer, which can run on Linux or Windows, connects to the PLC via MODBUS and manages configuration, HTTP server, and database functions. The system can be monitored and controlled remotely via HTTP clients through an internet- connected network.

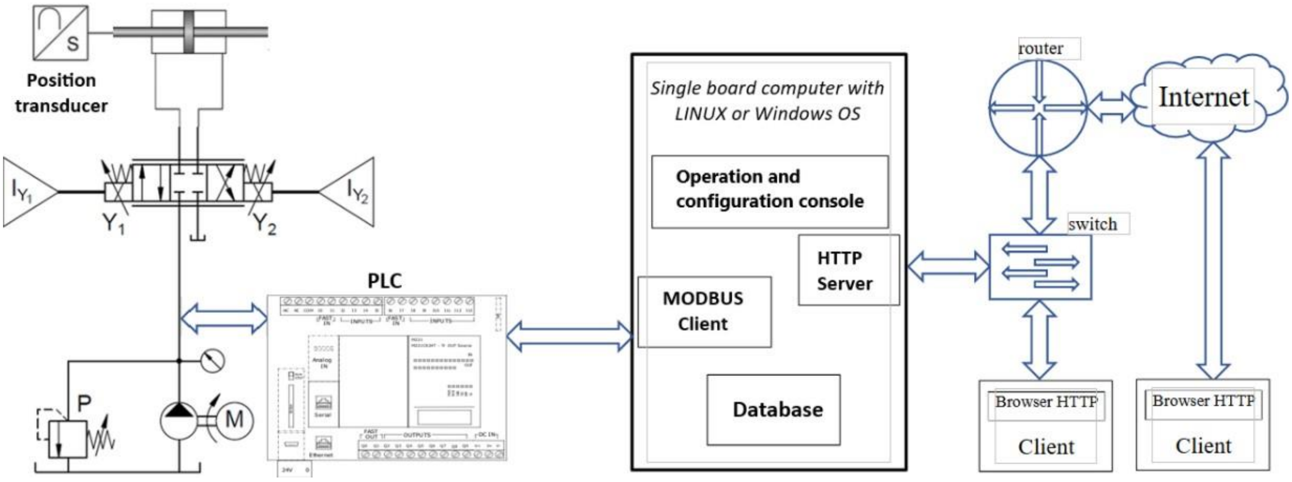


Fig. 4. Block diagram of the IoT system

4. Experimental setup

Fig. 5 and **fig. 6** illustrate the experimental stand, controller and other equipment used for the testing of 2-DOF controller on a hydraulic system. **Fig. 7** shows the functional diagram of setup.

Fig. 5. Experimental stand

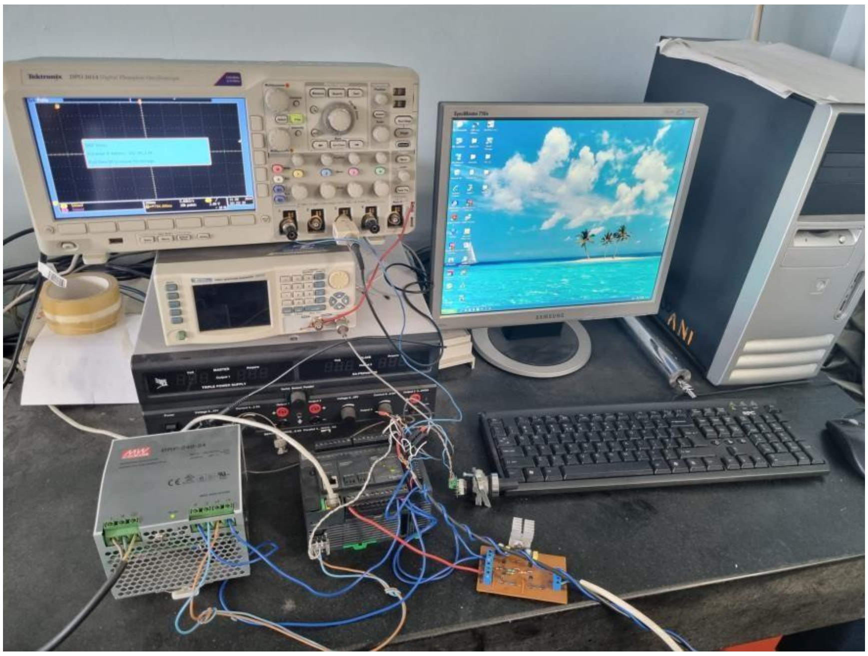


Fig. 6. Controller setup, with waveform generator and computer

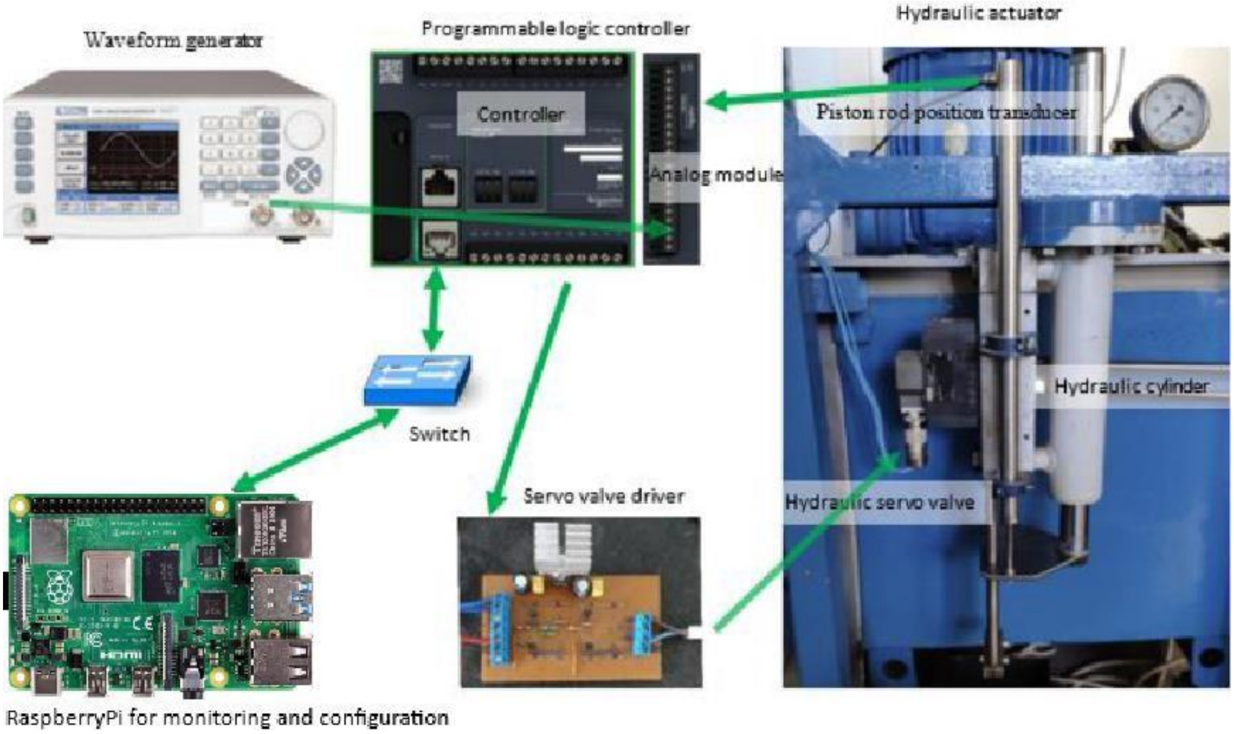


Fig. 7. Functional diagram of test stand

The hydraulic cylinder is actuated by an electro-hydraulic flow servo valve, which is powered by a hydraulic station capable of providing a pressure of 150 bar and a flow rate of 60 liters per minute. This setup enables a maximum speed of 0.66 meters per second and a maximum force of 1100 daN at the hydraulic cylinder rod. The position of the cylinder rod, with a maximum stroke of 200 mm, is monitored using an LVDT-type position transducer with a measurement range of 200 mm. Control signals for the linear hydraulic axis are generated by a WW5061-TABOR ELECTRONICS digital signal generator, facilitating the evaluation of both the static and dynamic performance of the hydraulic axis.

5. Results

The following pictures illustrate system response (cylinder rod position, error and velocity) when applying sinusoidal, step and triangular reference.

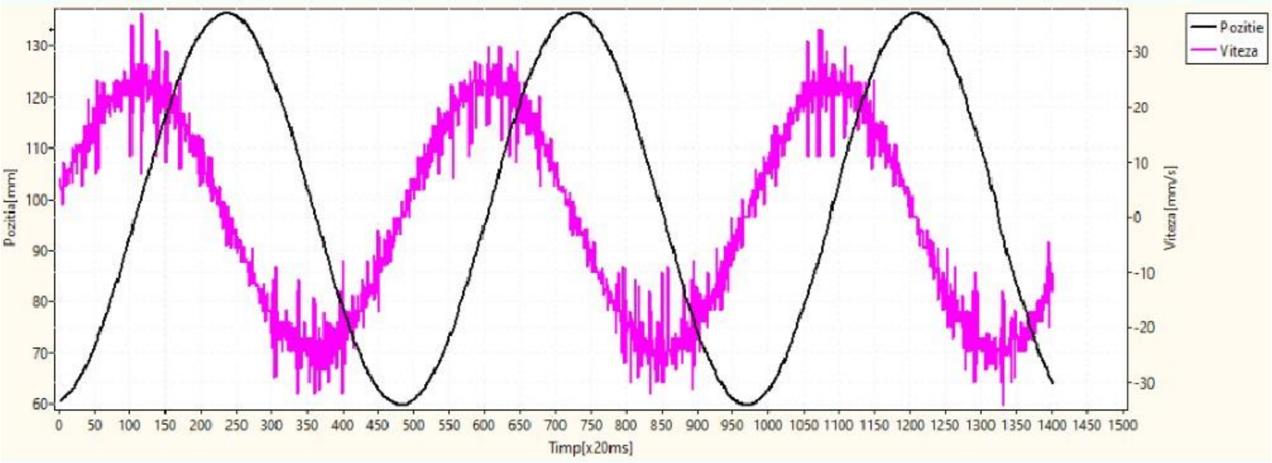


Fig. 8. Cylinder rod position (black) and velocity (purple) for sinusoidal signal

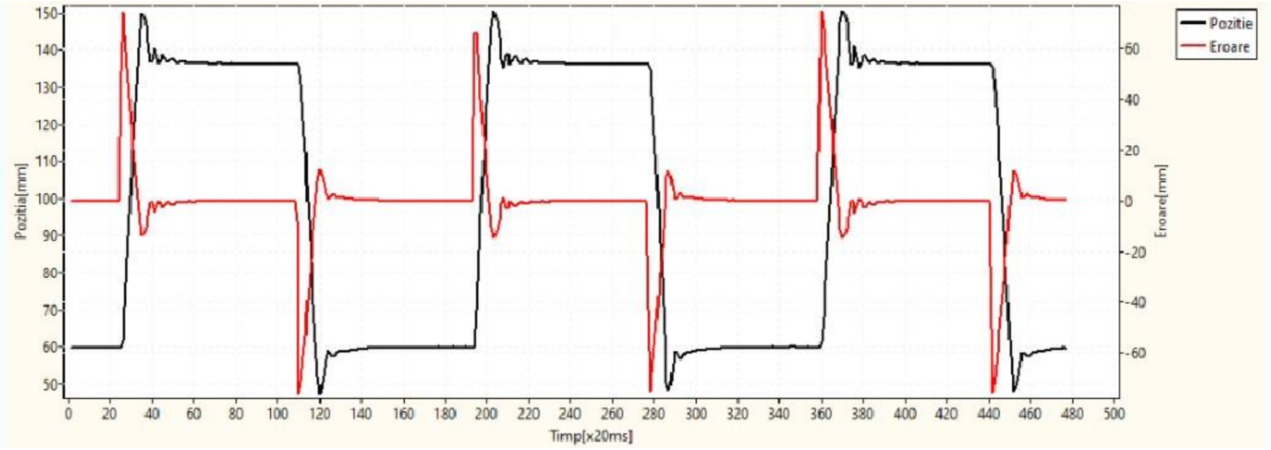


Fig. 9. Cylinder rod position (black) and error (red) for step signal

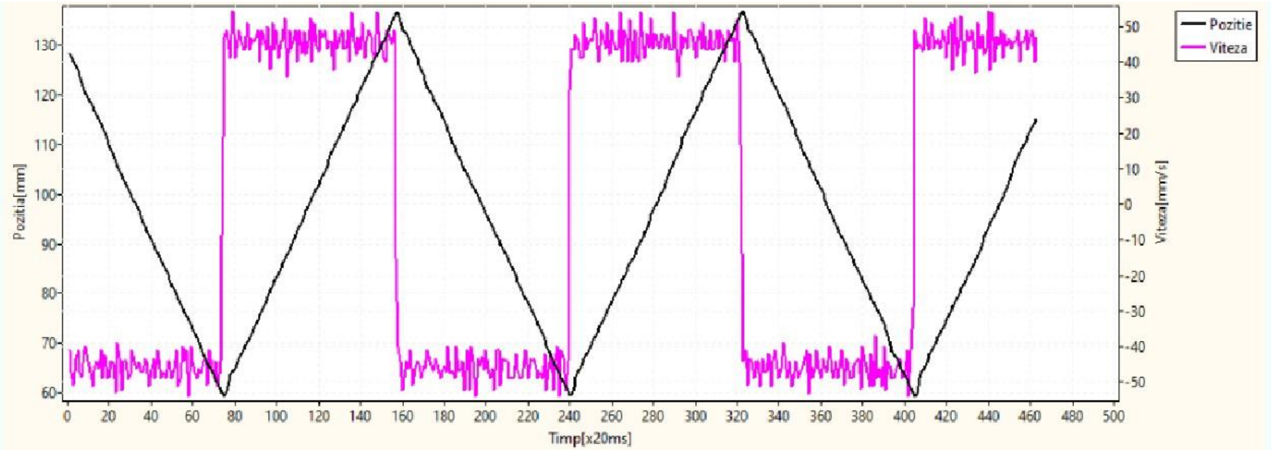


Fig. 10. Cylinder rod position (black) and velocity (purple) for triangular signal

For **fig. 8**, position shows a smooth sinusoidal pattern indicating periodic motion. The velocity data is noisy but follows a periodic pattern as well, peaking when the position changes the fastest, which is consistent with the derivative of a sine wave.

In **fig. 9**, the error spikes at the same time as the rapid transitions in position, which is typical as the system responds to changes and attempts to correct for deviations from the desired position. For **fig. 10**, the velocity is highly variable and noisy but shows clear peaks at the points where the position changes direction, resembling a step-like pattern.

6. Conclusions

In the presented material, it was demonstrated how a linear hydraulic axis can be improved into an IoT system using open-source software and general use hardware. Thus, the client can monitor and parametrize the hydraulic axis from the network based on a dashboard, through any general-use browser. As a suggested direction for continuing the research, the development of new cloud - based businesses can be considered, offering access to the hydraulic axis through software applications commercialized in the form of software as a service (SaaS). Additionally, the IoT system could detect real-time operational anomalies of the hydraulic axis and can send alerts to users or trigger preventive or corrective actions. Another suggestion involves integrating a database into the client software, where values and process parameters are stored in real-time, allowing the monitoring of the system's evolution over time.

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