PLC IMPLEMENTATION OF 2-DOF CONTROLLER FOR HYDRAULIC DRIVES

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Abstract: *Two-Degree-of-Freedom control systems, abbreviated as 2-DOF, have two independent adjustable closed-loop transfer functions. One is feedback type PID control (proportional – integral – derivative) and the other one is feedforward type control. This kind of control combines the advantage of feedback and feedforward type controllers. On the other hand, the accessibility of programmable logic controller, abbreviated as PLC, with real-time signal processing performance for the control of fast systems (such as hydraulic drives), enables the implementation of high-performance control algorithms that are executed in real time. The paper presents the software implementation in a common PLC of a 2-DOF type controller as well as its monitoring and parameterization software application.*

Keywords: *Hydraulic drive, actuator, controller, PLC*

1. Preliminaries

This chapter presents a brief introduction to the theory of control systems with two degrees of freedom used to implement the controller. The specific requirements for using 2-DOF controllers in hydraulic drives are also presented.

A general form of the 2-DOF control system is shown in fig.1, where the controller consists of two compensators *C(s)* and $C_f(s)$, and the transfer function $P_d(s)$ from the disturbance *d* to the controlled variable *y* is assumed to be different from the transfer function *P(s)* from the manipulated variable *u* to *y*. *C(s)* is called the serial (or main) compensator and $C_f(s)$ - the feedforward compensator [1].

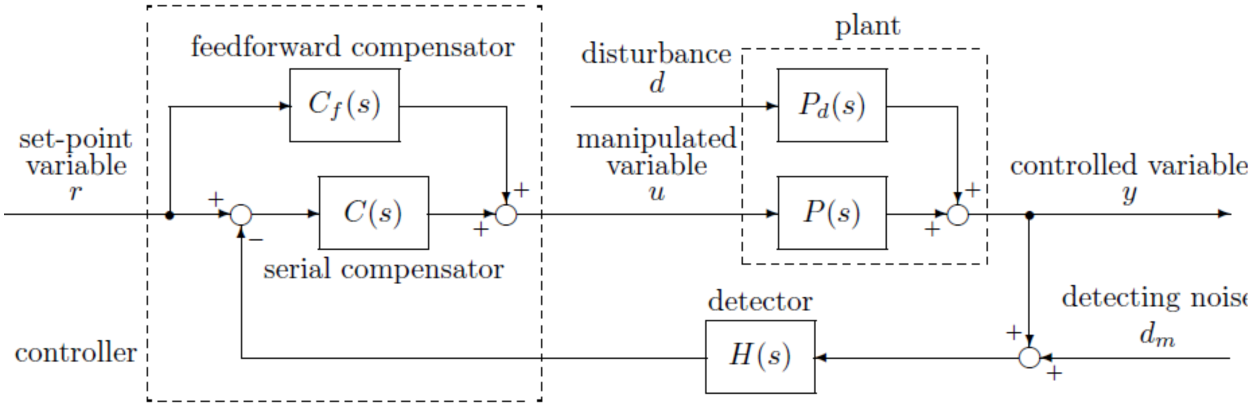


Fig. 1. Two degree of freedom (2-DOF) control system

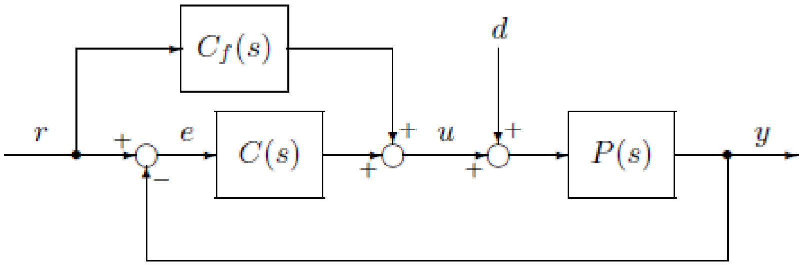
We consider that

$$H(s) = 1, d_m = 0 \tag{1}$$

and

$$P_d(s) = P(s) \tag{2}$$

Under these assumptions, (1) and (2), a 2-DOF PID control system is shown in fig. 2. Considering that the major advantage of the PID controller lies in its simplicity, it was proposed to include only the proportional and/or the derivative components in $C_f(s)$. The controller part is a two-input one-output system where the set-point variable *r* and the controlled variable *y* are the input signals and the manipulated variable *u* is the output signal. Thus the feedforward path from *r* to u is adding to the conventional PID command.



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

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

Fig. 2. Feedforward type of the 2-DOF PID control systems

Mainly, hydraulic drives have two types of actuators, position-controlled linear actuators and speed-controlled rotary actuators. For position-controlled linear actuators, it is necessary to calculate the feedforward path command as the derivative of the reference point because this command value (derivative of the reference point) is proportional to the speed of the manipulated variable ($\alpha=0$), while for speed-controlled rotary actuators the feedforward path command is proportional to the set-point value because the actuators speed (manipulated variable) is also proportional to it ($\beta=0$).

2. Controller implementation - PLC software and hardware

Modicon IIoT-native edge controllers manage complex interfaces across assets and devices or directly into the cloud, with embedded safety and cybersecurity. Modicon provides performance and scalability for a wide range of industrial applications up to high-performance multi-axis machines and high-available redundant processes [2]. Modicon M221, an entry-level PLC, was used to implement the 2-DOF PID control algorithm. The software development platform for this PLC is EcoStruxureMachine Expert - Basic, free licence, programing software for M221 controllers.
The hardware platform was built around a TM221CE24T controller with the following characteristics: 14 digital inputs, 10 sources transistor outputs (0.5 A), 2 analog inputs, 1 serial line port, 1 Ethernet port, 24 Vdc power supply controller with removable terminal blocks. A TM3AM6 analogic expansion module is required to interface the actuator with the PLC. TM3AM6 has the following characteristics: 4 analog inputs (+- 10 V, 0-10V, 0-20 mA, 4-20mA) and 2 analog outputs (+- 10 V, 0-10V, 0-20 mA, 4-20mA), 12 bits, removable terminal blocks.
The program running on the PLC implements the operation of the 2-DOF controller and is developed in the ladder diagram language. Thus, the configuration of the controller is established by positioning some bits such as:
- enabling feedforward control
- enabling feedback control (PID or PI+feedforward)
- enabling S-curve generator [3] on set-point path
- sign reversal enabled for controlled variable
- derivative value of set-point for feedforward control, default is set-point value

The value of the process command, manipulated variable, is:

$$u(t) = K_P * [err(t) + T_D * \frac{d\,err(t)}{dt} + \frac{1}{T_I} * \int_0^t err(\tau)d\tau] + K_F * [\frac{d\,sp(t)}{dt}; sp(t)] \qquad (3)$$

where if feedforward control is enabled then $T_D=0$ and $K_F<>0$ else $T_D<>0$ and $K_F=0$.
Other parameters of the controller that can be set by the user are:
- proportional gain K_P
- derivative time T_D (if feedforward is disabled) or feedforward transfer factor K_F (if feedforward is enabled)
- integral time T_I
- proportional weight
- derivative weight
- integral weight
- maximum error for reference (if S-curve generator is enabled)
- maximum speed for reference (if S-curve generator is enabled)
- maximum acceleration for reference (if S-curve generator is enabled)
- maximum jerk for reference (if S-curve generator is enabled)
- scaling factor for reference an controlled variable values
- scaling factor for speed
- scaling factor for acceleration
- scaling factor for jerk

The establishment of these values is carried out through the Ethernet interface of the controller using the MODBUS over TCP/IP protocol.

3. Controller monitoring and parametrization - PC software

To monitor and parameterize the 2-DOF controller, it was necessary to develop a software that runs on a computer located in the same network as the controller. It was developed using the Lazarus free programming environment and the Free Pascal programming language [4].
The software main window is shown in fig. 3. This window enables one to monitor the process parameters in graphical form, measuring the values on the graph as well as viewing the controller configuration and the state of communication with it.

Fig. 3. PC software – main window

Fig. 4 shows the window of the program that allows the establishment of the functional parameters of the 2-DOF controller.

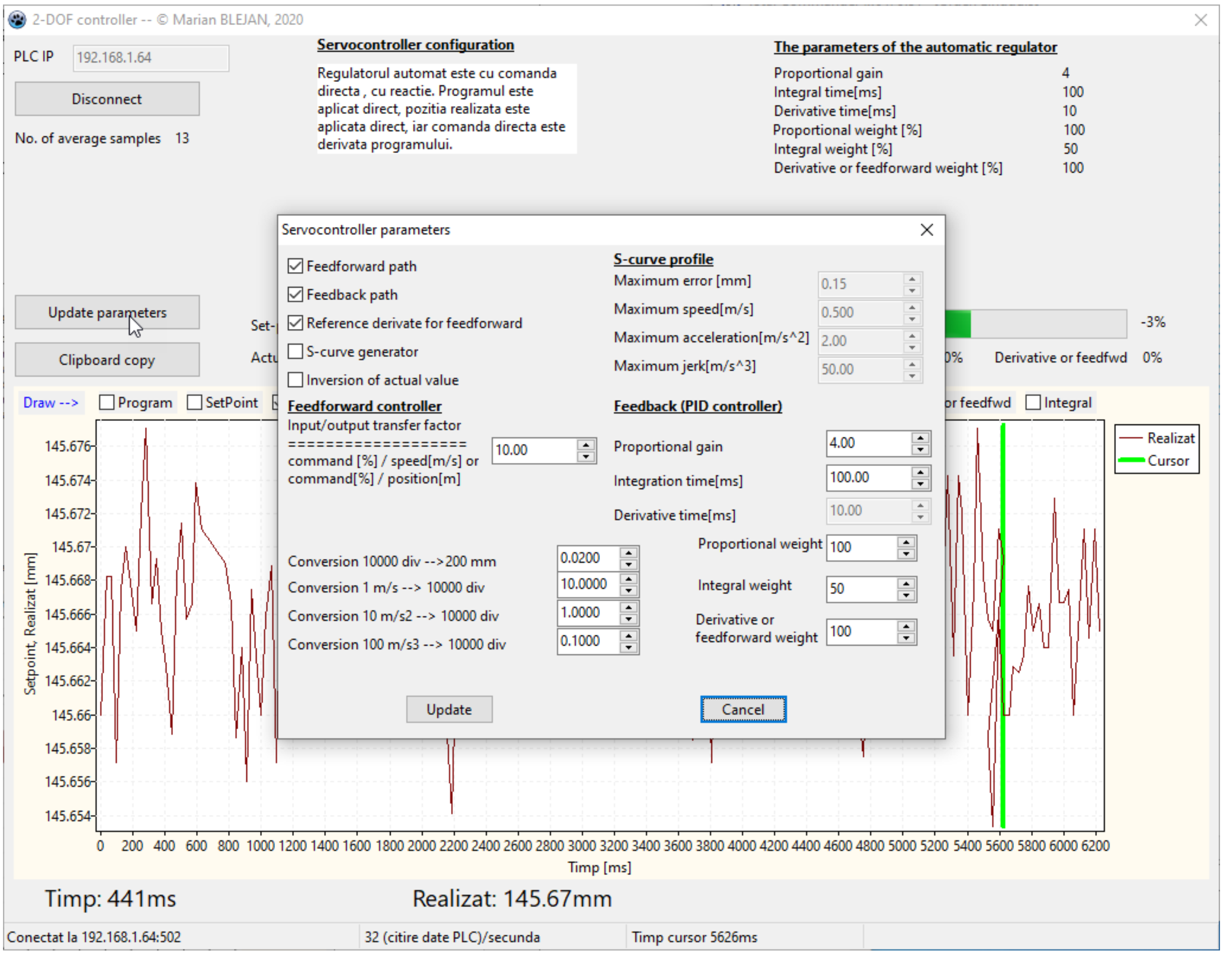


Fig. 4. PC software – 2-DOF controller parameters window

4. Experimental setup

The presented controller was tested on the experimental setup shown in fig. 5 and fig. 6, respectively on a position-controlled linear actuator.

Fig. 5. Experimental stand

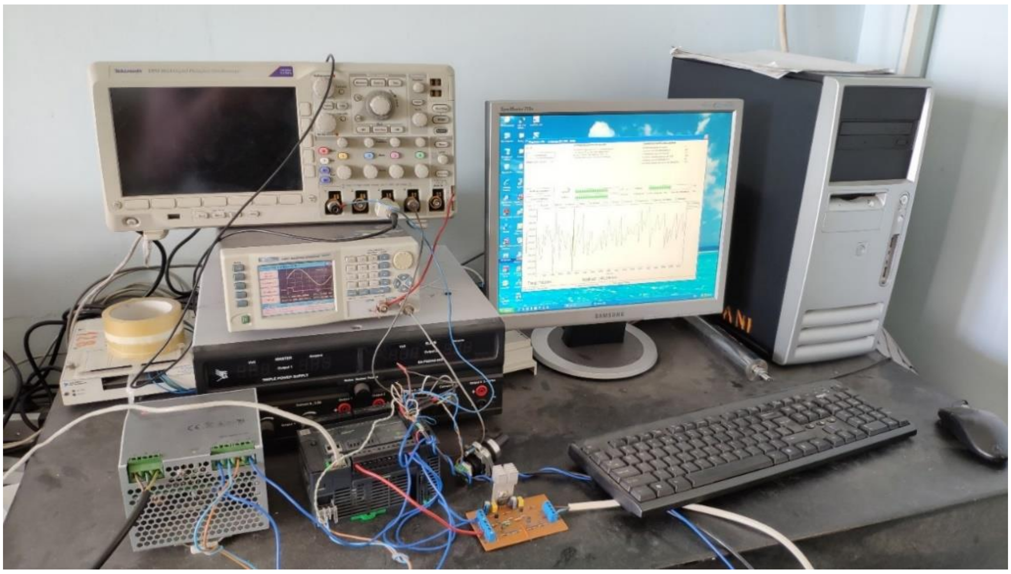


Fig. 6. Controller, waveform generator and PC

Fig. 7 shows the functional diagram of the test stand.

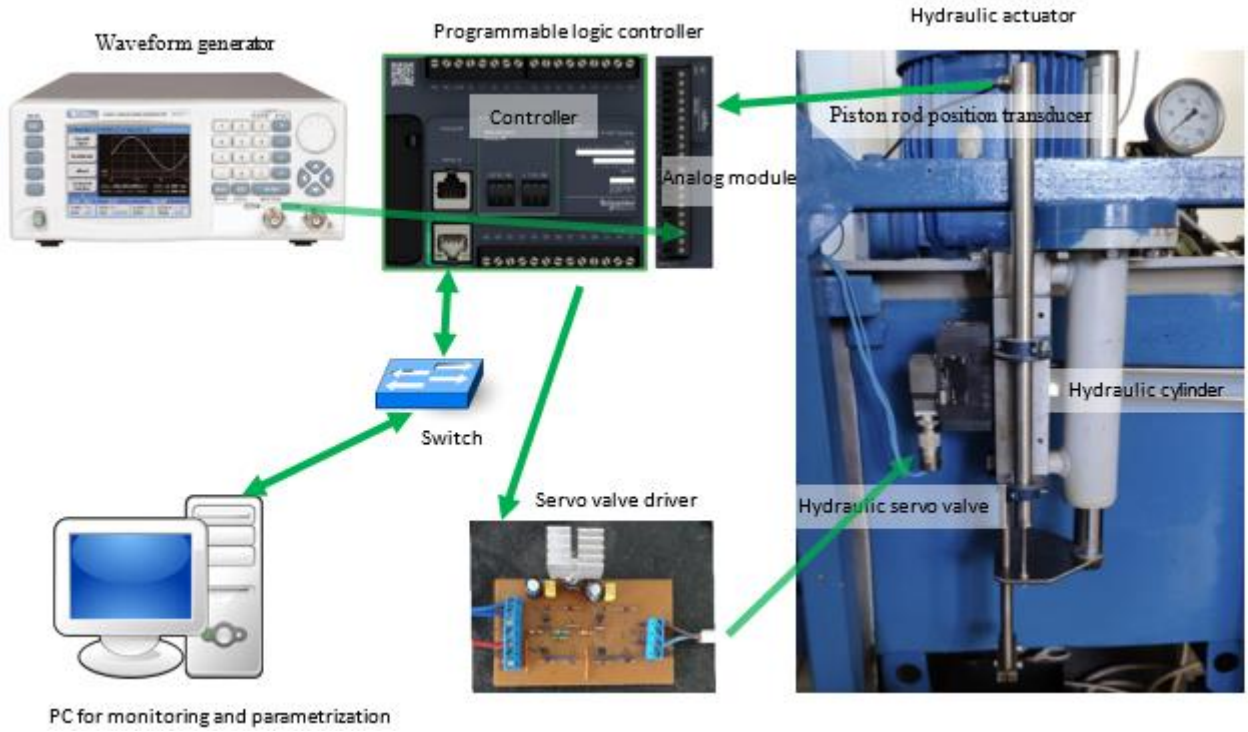


Fig. 7. Experimental stand diagram

The hydraulic cylinder is actuated by an electrohydraulic flow servo valve powered by a hydraulic station capable of providing a pressure of *150 bar* at a flow rate of *60 litres/min*, which allows a maximum speed of *0.66 m/s* to be obtained and a maximum force whose value is *1100 daN* at the level of the hydraulic cylinder rod. The position of the cylinder rod, which has a maximum stroke of *200 mm*, is monitored with the help of an LVDT type position transducer with a measurement range of *200 mm*. The control signals of the linear hydraulic axis are generated with the help of a WW5061 - TABOR ELECTRONICS digital signal generator [5] and allow the evaluation of the performance of the static and dynamic regime of the hydraulic axis.

5. Experimental results

To evaluate the position control performance of a hydraulic linear actuator, a step reference signal was applied and the response of the actuator was monitored.

Fig. 8. Set-point and actual value of position, *70 mm* step, 1-DOF PID regulator $K_P=4$, $T_I=100$ ms, $T_D=10$ ms

Fig. 9. Set-point and actual value of position, *70 mm* step, 2-DOF PI regulator $K_P=4$, $T_I=100$ ms, $K_F=10$

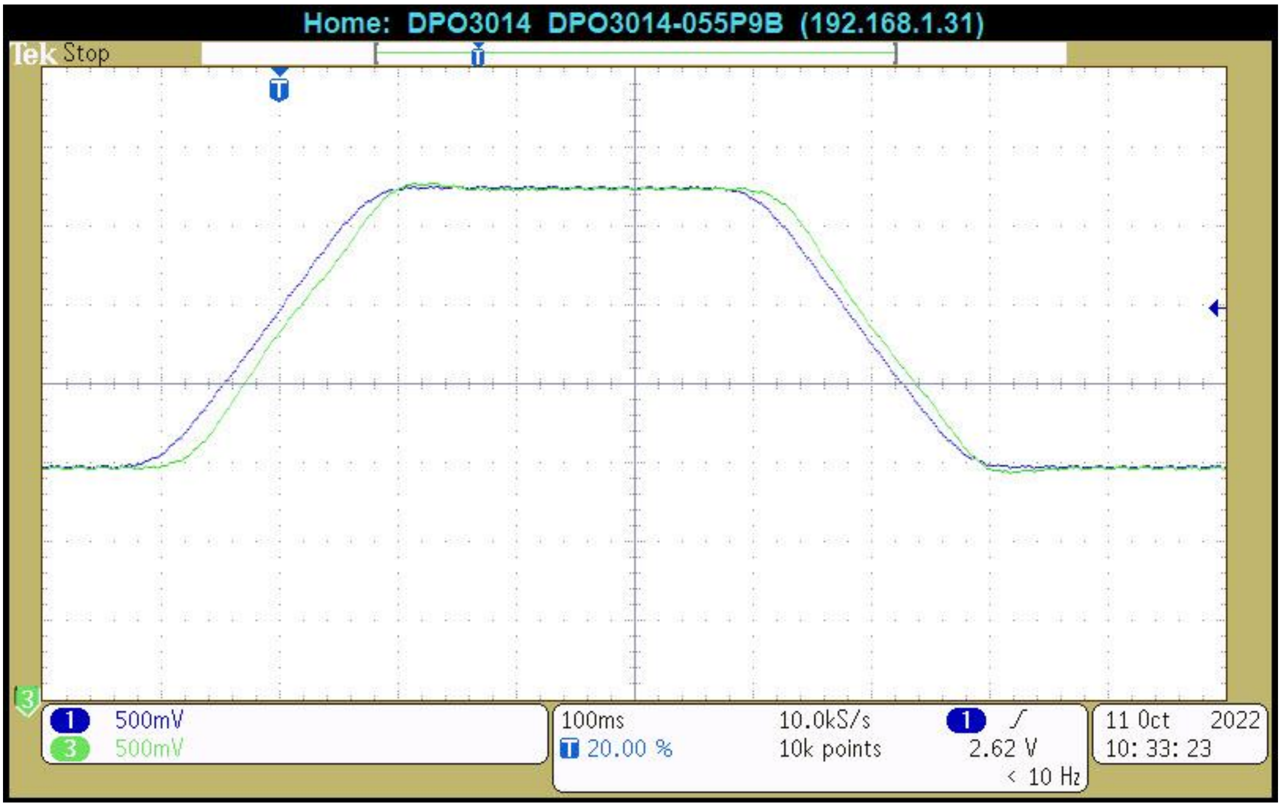


Fig. 10. Reference and actual value of position, *70 mm* step, 2-DOF PI regulator and S-curve generator on set-point path K_P=4, T_I=100 ms, K_F=10, v_{max}=0.4 m/s, a_{max}=20 m/s2, j_{max}=175 m/s^3

Three tuning algorithms were used: 1-DOF PID feedback (fig. 8), 2-DOF feedforward and PI feedback (fig. 9), respectively 2-DOF feedforward, PI feedback and S-curve generator on the set-point path shown in fig. 10. The blue trace is the reference position and the green trace is the actual position.
The maximum pressure of the hydraulic group is set to *50 bar*, which allows a maximum speed of *0.5 m/s* without load.
1-DOF PID feedback shown in fig. 8 has an aperiodic response with a rise time of *200 ms*. 2-DOF feedforward and PI feedback, fig. 9, has a periodic response with a rise time of *150 ms* and *3.5 mm* overshot (*5%* of step value of *70 mm*), while 2-DOF PI regulator and S-curve generator on set-point path (fig. 10) has an aperiodic response with a rise time of *160 ms*.

6. Conclusions

The two-degree-of-freedom controller developed as software on PLC hardware support has experimentally confirmed its functional performance in the field of hydraulic drives obtained by using advanced control algorithms. The authors have also demonstrated the functionality of the PC software for controller monitoring and parameterization.

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