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DEVELOPMENT OF A LOW COST AUTOMATED VALVE FOR FLUID LEVEL CONTROL IN COMMUNICATING VESSELS

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Abstract. *The aim of the present work was to develop a low-cost valve built from a servomotor and an ordinary commercial valve, made of cast iron. A structure built by a 3-D printer, using a thermoplastic material - ABS (Acrylonitrile Butadiene Styrene) was developed in order to mechanically connect the valve to the servomotor. An FEA (Finite Element Analysis) was carried out in order to optimize the printed structure. A PIC 12F675P – 8-bit microcontroller - was employed to control the servomotor axle position and to allow the communication of the valve with a PLC (Programmable Logical Controller). The valve was tested in a reduced scale plant that represents a continuous industrial process with communicating vessels where a PID (Proportional-Integral-Derivative) control technique was applied.*

Keywords: *Reduced scale plant, fluid level control, communicating vessels, continuous process*

1. INTRODUCTION

Industrial continuous processes often require modelling non-linear systems in order to represent communicating vessels, where the fluid level, temperature as well as a pre-determined concentration of composes must be strictly controlled (Ogata, 2010). In addition, reduced scale plants can be used either to validate or to improve the mathematical models of real systems. In those cases, the control of the fluid level, the mass and energy moving in and out of the vessels can be achieved by implementing automated valves where techniques such as PID can be employed. For the model developed in the present work, the adjustable flow rates, between 0% and 100%, will be proportional to the signal applied to valve controller. The use of automatic valves in reduced scale plants might be prohibitive in some cases due to the high cost of these control elements. In order to create an alternative to the products available in the market, the present work proposes a feasible low cost solution and describes the steps to build an automated valve from an ordinary commercial cast iron ball valve, mechanically connected to a servomotor by thermoplastic structure built by a 3-D printer. The 3-D printing enables small quantities of customized goods to be produced at relatively low costs (Berry, 2012). The thermoplastic employed in this case was the Acrylonitrile Butadiene Styrene (ABS), which has melting temperatures low enough to be used in melt extrusion outside of a dedicated facility, while high enough for printed objects to retain their shape at average use temperatures (Tymrak, *et al.,* 2014). This terpolymer is a member of the styrene family. The properties of a particular ABS resin will depend on the blend ratio of the three major constituents, Acrylonitrile, Butadiene, and Styrene (Ibeh, 2011).

A PIC 12F675P, 8-bit microcontroller, is used to control the servomotor axle position through PWM (Pulse Width Modulation) technique, and hence it will manage the flow through the pipe as well as the fluid level in the tanks. The PIC microcontroller allowed the communication between the valve and a PLC.

2. MATERIALS AND METHODS

The development process was divided in two blocks: Analytical and experimental. In the analytical scope, several servomotors available in the market were analyzed using the datasheet from the manufactures, based on the valve torque requirements linked to the flow to be controlled. In this case, the model Track Star TS-700 MG was chosen. It presents a good torque range for the proposed application, from 2.72 Nm (at 4.8 V) to 3.3 Nm (at 6.0 V), and a fast angular speed response, from 5.3 rad/s (at 4.8 V) to 5.8 rad/s (at 6.0 V). In addition, an ordinary ball valve of ½” size was selected, with low friction coefficient, from 0° to 90° total angular range, manufactured by DECOL. An 8-bit PIC microcontroller from 12F Microchip family, model 12F675P, was selected. This MCU has an 8-pin architecture package with a 10-bit ADC (Analog to Digital Converter) featured with 4 channels. The firmware of the MCU was developed using the MikroC Pro for PIC, and the interrupt technique, based on timer (T0IF) overflow, was employed to modulate the pulse width in the servo control pin. The registers of the MUC analog inputs were enabled for the AN0 pin in order to establish the communication with the PLC.

In the experimental block, components and circuits were tested in order to check the plausibility of the real system behavior compared to the simulation results, mathematical models and specifications described on datasheets. For example, as a means to define the servomotor frequency of operation, an arbitrary waveform function generator RIGOL DG1022A was employed. The servomotor worked at approximately 60 Hz, and hence, this was the frequency employed in the PWM signals controlling the servo.

2.1 3D Printed mechanical structure

The valve and the servomotor selected were modeled with SolidWorks 2016 in order to provide the basis for the design of the mechanical link. The connection was developed considering the ABS thermoplastic mechanical properties already available in the SolidWorks material database: Tensile strength of 30 MPa and elastic module of 2000 MPa. The structure connecting the servo and the valve is bipartite and coupled together with M6 bolts. This feature allows small dimensional variations on the valve body to be absorbed by the bipartite structure.

An FEA was conducted in order to analyze the structure behavior when subjected to the efforts applied by the servomotor. These efforts were defined based on the maximum torque delivered by the servomotor, which is 3.3 Nm. The Maximum distortion energy theory, or Von-Misses criteria (Hibbeler, 2006), was used in this case since ABS thermoplastic material may be considered ductile (Ibeh, 2011). Depending on the composition, elongation at breaking point may vary from 5% to 30% (Ibeh, 2011), the tensile strength from 27.6 MPa to 29.7 MPa and the elastic Modulus from 1807 MPa to 1875 MPa (Tymrak, *et al.*, 2014). The result of the analysis is shown in Fig. 1 and Fig. 2.

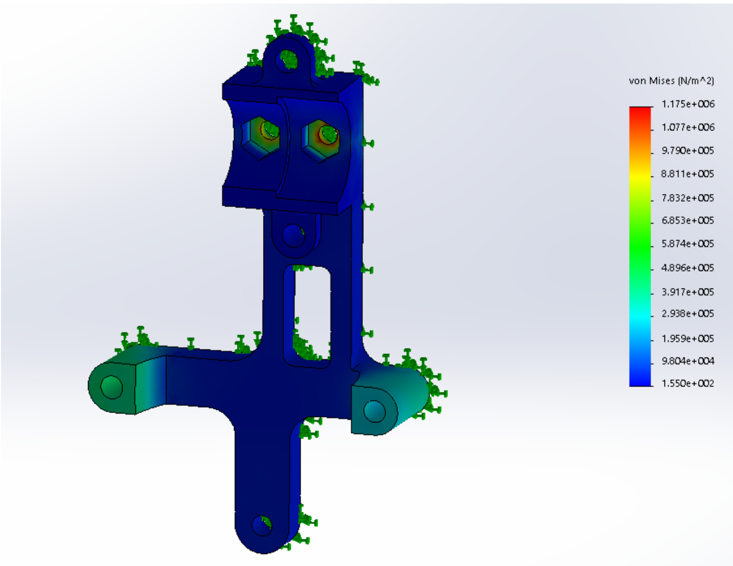

Figure 1. Mechanical connection FEA analysis

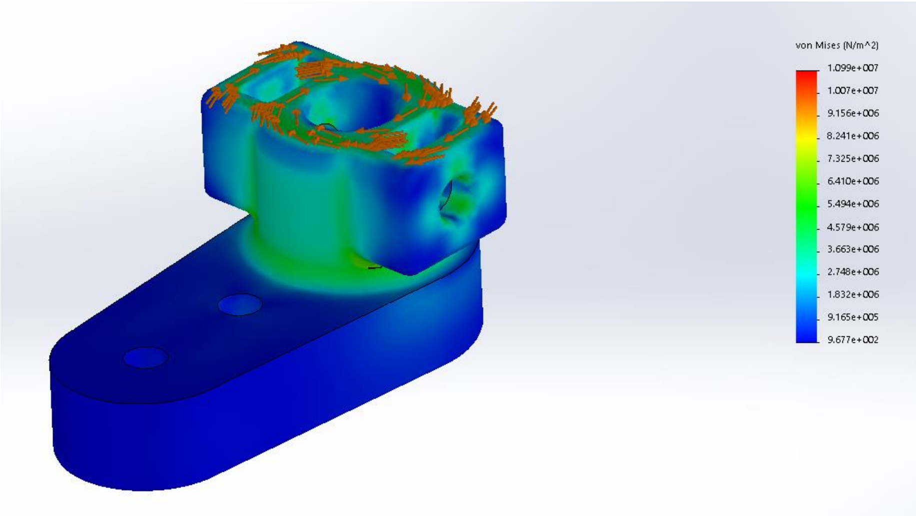

Figure 2. Valve and servomotor axle connection FEA analysis

It must be pointed out that the mechanical properties of the components built from a 3-D printer are highly affected by the printer settings such as extruder and print bed temperature, nozzle diameter, cooling, print speed, layer height and the material deposition orientation (Tymrak, et al., 2014). For example, observation has shown that 5°C temperature variation in the material causes visible quality differences of a 3-D print, which is assumed to change the mechanical strength as well (Tymrak, et al., 2014). In this case, the FEA results must be carefully interpreted, and for the application proposed in the present work, they were mainly used to optimize the structure allowing material to be removed from the parts where low stress levels were observed.

2.2 Electronic circuit

The electronic circuit with a PIC 12F675P was simulated using Proteus ISIS 8.1. A 20 MHz crystal was employed as an external oscillator in order to drive the MCU clock. The crystal was connected to the OSC1 and OSC2 pins in parallel with two 30 pF ceramic capacitors to increase the stability of the oscillator, according to the MCU manufacturer recommendations. The Master Clear fuse was enabled. It was connected to the +5 V source with a 10 kΩ resistor to limit the current. A 1 kΩ potentiometer was used to manipulate the voltage through the input pin AN0 to reproduce the analog signals coming from the PLC. The simulation circuit with ISIS Proteus is shown in Fig. 3. The control circuit of the servo is shown in Fig. 4.

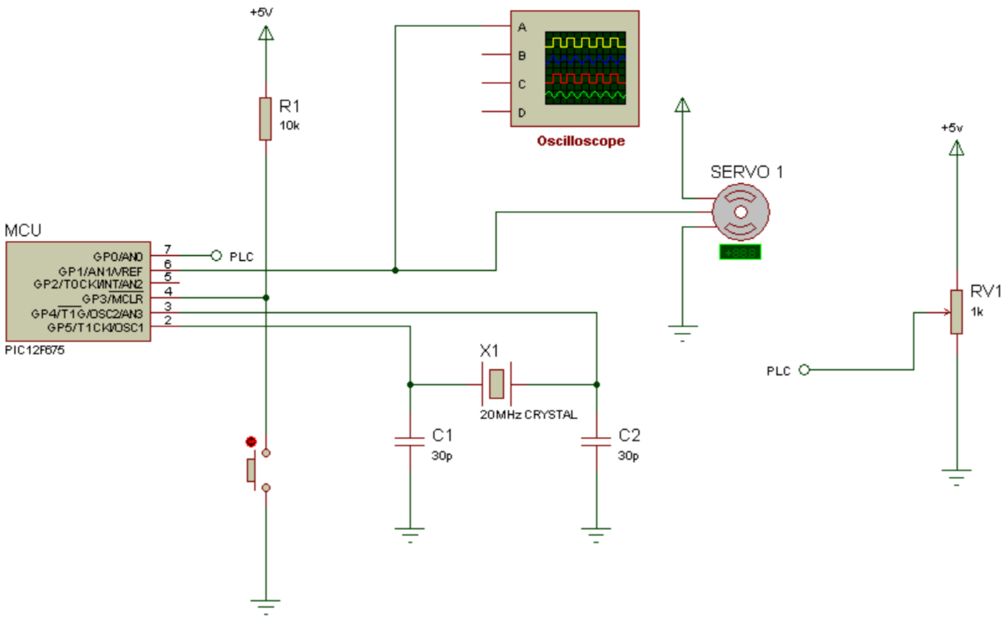

Figure 3. Servomotor circuit simulation using ISIS Proteus 8.1

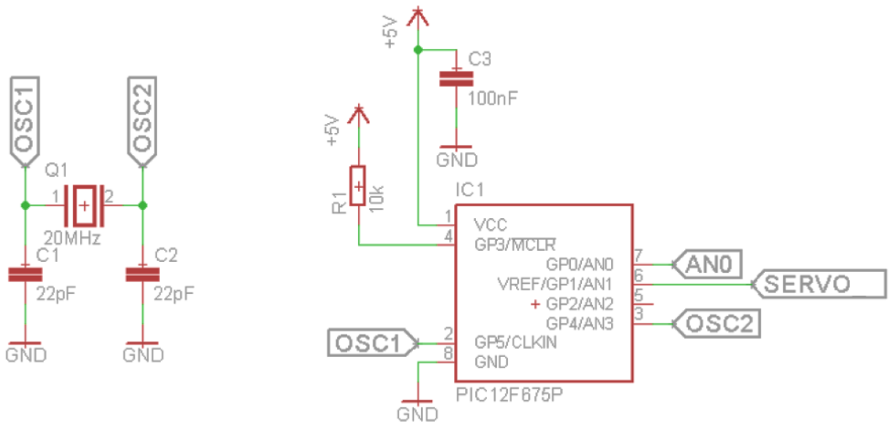

Figure 4. Servomotor control circuit schematic diagram

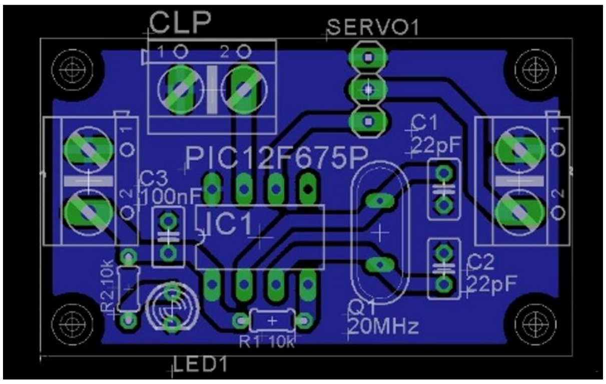

Figure 5. Circuit designed to control the servomotor axle position

3. RESULTS AND DISCUSSIONS

The final 3D assembly is shown in Fig. 6. The details of the link between the servomotor and the valve axle are shown in Fig. 7. The final product assembled and installed is shown in Fig. 8.

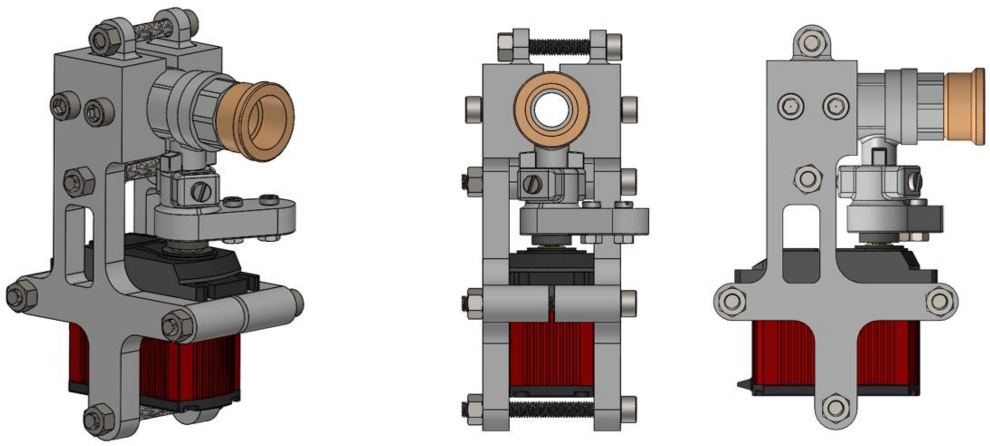

Figure 6. Automated valve 3D model - Final assembly

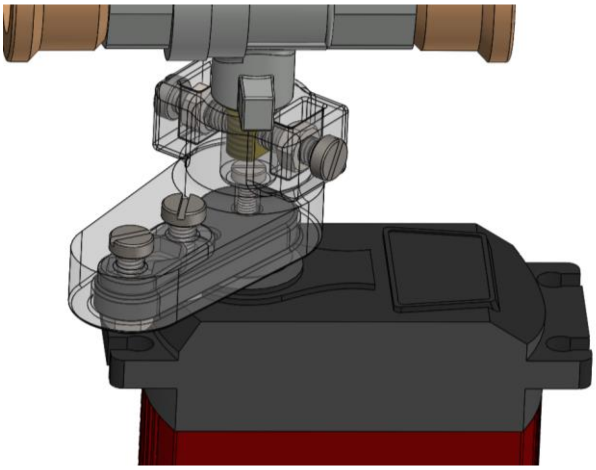

Figure 7. Details of the connection between the valve and the servomotor

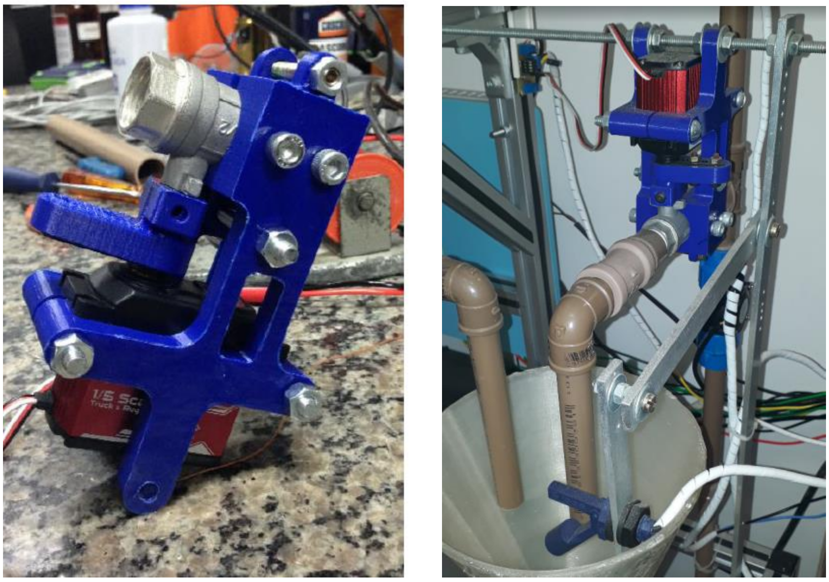

Figure 8. Low cost proportional valve final assembly

The valve was installed and tested in a reduced scale plant with communicating vessels in a closed loop PID control block. A frequency inverter Power Flex Mode 70AC was employed as a means to manipulate the flow as well as the pressure through the pipeline. A maximum flow of $3.33x10^{-4}$ m^3/s (20 l/min), measured through FSA30004 G3/4” sensor, was used. The maximum pump head was indirectly calculated through the pump performance curves and similarity rules (White, 2010), and in this case, was 2.0 mWG. A pump manufactured by Dancor, model W4-NE 1/2CV, was utilized to provide energy to the fluid. The PLC used to test the valve was a Compact Logix, Allen-Bradley, series 1769 L32E, with an output analog module 1769-OF4. The PIC 12F675P, receives the analog signal from the PLC, properly conditioned through the function “Scaled for PID” in the RS Logix Ladder Program. Hence, the analog signal is converted by an onboard 10-bit ADC, where the position of the valve, from 0° (totally closed) to 90° (totally open), is proportional to the ADC values. The 3-Dmodel of the plant where the valve was tested is shown in Fig. 9. The pressure sensor MPX5010DP was adapted to monitor the fluid level in the three vessels. The output of the pressure sensor is sent to the PLC module 1769-IF8. The sensor output response is proportional to the measured pressure, varies from 0.2 V to 4.7 V, and is converted in the fluid level by the Ladder routine.

Figure 9. Rendering of the plant model where the valve was validated

Taking the squared base prismatic tank to demonstrate the tests conducted, the first step was to develop the phenomenological model considering the variation of the fluid level in the vessel as a function of the fluid flowing in and out the control volume. The base of the tank measures 20 cm per 20 cm, and the height, 40 cm. The control volumes considered are shown in Fig. 10.

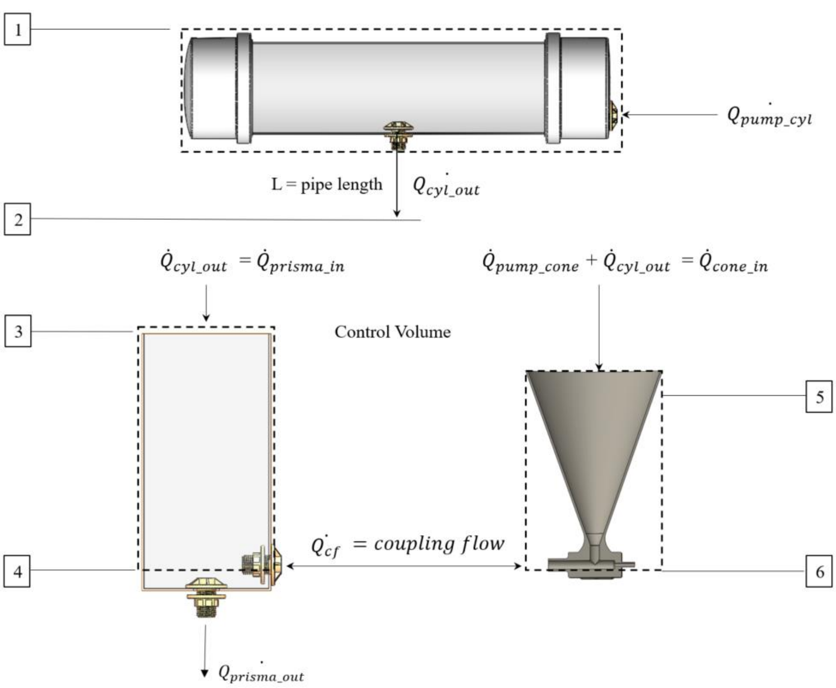

Figure 10. Control volumes of the system

Considering $S(h)_{prima}$ the cross-section surface of the vessel as a function of the fluid level h_{prisma}, in this case, $S(h)_{prima}$ will be constant and represented by S_0. S_{pipe} is the cross-section surface of the pipeline, and then, the mass flow balance in the prismatic tank is given by Eq. (1).

$$\frac{dh_{prisma}}{dt} = \frac{1}{S_0} \times \left(\dot{Q}_{cyl\_out} - \dot{Q}_{prisma} - \dot{Q}_{cf} \right) \quad (1)$$

The flow coming out from the cylinder tank will be given by Eq. (2) and the flow coming out from the prismatic vessel will be given by Eq. (3).

$$\dot{Q}_{Cyl\_Out} = S_{pipe} \times \sqrt{2g \times (h_{cyl} + L)} \tag{2}$$

$$\dot{Q}_{prisma} = S_{pipe} \times \sqrt{2g \times h_{prisma}} \tag{3}$$

Where Q_{cyl_out} is volume of fluid coming from the cylindrical vessel and flowing to the prismatic tank, h_{cyl} is the fluid level in the cylindrical vessel, L is the vertical distance from the cylinder output to the pipe where the valve is placed and Q_{cf} is the coupling flow between the prismatic and conical vessels.

The coupling flow between two communicating vessels is, then, given by Eq. (4) (Smith and Corripio, 1985):

$$Q_{cf} = S_{pipe} \times \sqrt{2g \times (h_{prisma} - h_{conical})} \tag{4}$$

The mathematical model was, then, translated to the Simulink block programming in order to simulate the behavior of the prismatic vessel system when it is subjected to a change in the setpoint, provoked either by a disturbance or by a change in the operating point. These changes were represented by a step function. The following assumptions were considered in this case: The level of the prismatic tank, h_{prisma}, is always greater than or equal to the level in the conical vessel, $h_{conical}$. The coupling flow was not included in modeling in order to simplify the simulation, however, it was considered in the system as a Gaussian noise. The feedback control loop does not know, nor does it care, which disturbance that enters in the process. It tries only to maintain the controlled variable at set point and in so doing compensates for all disturbances (Smith and Corripio, 1985).

The program developed in Simulink is shown in Fig. 11 and the resulting identification may be seen in Fig. 12. In this case, the linearization at the operating point was performed in order to draw the transfer function. The result of the simulation is shown in Fig. 13.

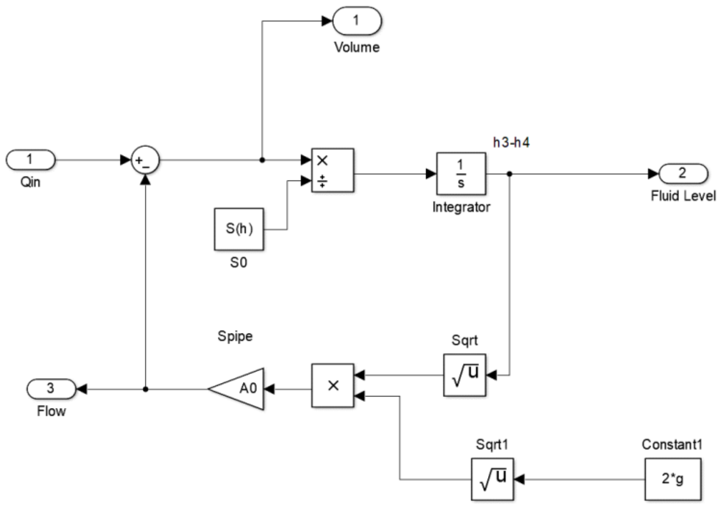

Figure 11. Prismatic squared base tank - simulation

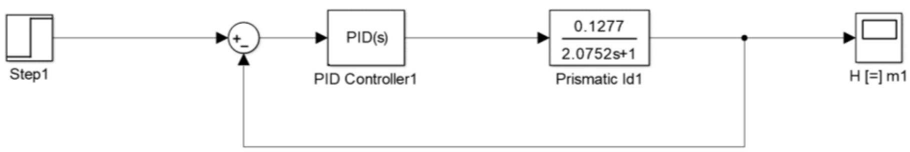

Figure 12. Prismatic squared base tank - identification

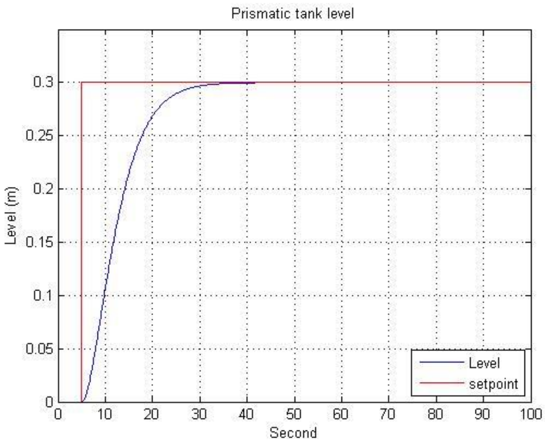

Figure 13. Prismatic squared base tank with tuned PID

In order to implement the PID control in the PLC, the tuning needed to be performed. In this case, the integral squared error (ISE) criteria was employed to optimize the controller. The gains obtained for the controller block of the prismatic tank were: k_p = 0.0008 (Proportional), k_i = 1240.53 (Integral), k_d = 0.

A graphical user interface was not developed at this point. Then, in order to illustrate the system working in practices, the PID block in the Ladder routine is shown in Fig. 14, where the current setpoint and the process variable may be seen for a particular operation point arbitrarily defined. Finally, the valve working in the plant is shown in Fig. 15.

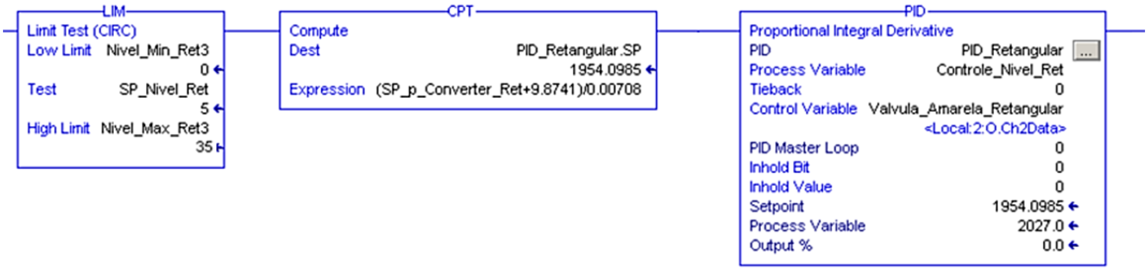

Figure 14. Ladder Routine showing the PID block with the setpoint and current value of the process variable

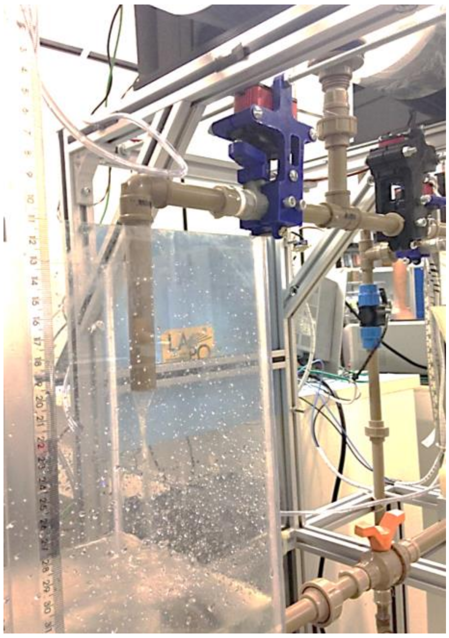

Figure 15. Valve tested in the prismatic vessel

4. CONCLUSIONS

The proposed valve proved to be an excellent low cost alternative where no high pressures are involved in the process, such as the application in reduced scale plants used to validate mathematical models. Taking, as an example, a product available in the local market, the Posiflow proportional solenoid valve, ½” size, manufactured by ASCO, brass body, 8 W, operation pressure from 30 kPa to 960 kPa. One unit of this model may cost around R$ 3193.00 (quoted directly from supplier *Central Brasileira de Automação*, at *NEI store - http://www.nei.com.br*, quotation received on September 28th, 2017). The proposed valve will cost from 10% to 20% the price of the mentioned commercial valve.

There is still the possibility to implement the valve as a standalone device, i.e., without the PLC, in a closed loop where the sensor monitoring the fluid level in the tank sends the signal directly to the MCU. In this case, a MCU with serial communication features, such as the 18F877A, can be implemented in order to send the data to a graphical user interface (GUI) running in an ordinary computer.

Control techniques such as PID were also successfully applied to test the valve functionalities even considering the coupling flow, between the connected conical and prismatic tanks, being a Gaussian noise. The proposed valve also has the advantage that no minimum differential pressure needs to be applied in order to allow its operation.

Fatigue analysis should be conducted in order to determine the real resistance of the 3-D connection since cyclic efforts will be present in a typical closed loop control application. Especial attention must be paid to the parameters selected in the 3-D printer settings, which will cause important variations on the mechanical properties of the final structure. Furthermore, a full mechanical properties characterization of the ABS 3-D printed structure is needed in order to conclude the dimensioning process, and as a last step, make the automated valve available in the market.

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