COB-2021-0309
SLIDING MODE CONTROLLER OF A COMPACT HYDRAULIC PROPORTIONAL VALVE DEVELOPED FOR AN IN-PIPE CLEARANCE ROBOT

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Abstract. Obstruction of underwater oil pipes is a recurrent problem that results in time and economic losses for companies in the offshore petroleum extraction field. The Annelida robot consists in a wall-pressing inchworm type robot designed for inspection and cleaning of underwater oil pipes, also called risers. The robot moves inside the risers driven by a hydraulically actuated locomotive, based in a double-action actuator, whose "legs" connect internally to the pipe walls by means of a self-locking mechanism. The main actuator of the locomotives is powered by a compact electro valve with a regenerative circuit, specially designed for current application. The valve is a spool type, operated by a nonlinear solenoid. In this paper, the mechanical dynamics of the spool valve and its solenoid behavior are modelled. Further, a feedback linearization strategy is applied to compensate the solenoid nonlinearity, and a sliding mode controller is designed and applied to control the valve spool trajectory. These strategies were combined to guarantee a robust control of a system with high nonlinearities. The dynamic model and the proposed controller are applied in simulations and the results compared with that of a standard PID controller. The simulations results show that the sliding mode with feedback linearization controller is able to effectively control the spool system, even in the presence of nonlinearities in the solenoid, and that its behavior, when comparing by means of transitory parameters, is similar to that of a PID controller. Also, an experimental setup was built using a prototype of the hydraulic valve specifically designed and manufactured for this application. Experiments were conducted with the valve disconnected from a hydraulic unit, operating it in its opening and closing motion in open loop, aiming to evaluate the proposed dynamic model of the valve. The data obtained show that the dynamic behavior of the valve prototype presents is similar to that of the mathematical model used in the simulations. With the model evaluated, the proposed control strategy is considered apt to be implemented and tested in the valve prototype.

Keywords: Hydraulic valve control, hydraulic regenerative circuit, pipe clearance robotics, feedback control, digital control.

1. INTRODUCTION

The importance of petroleum in our civilization is universally known. Petroleum can be extracted in land oil basins, with technologies called onshore, a common method used in the United States, for instance; or in the deep seas, as it is done in Brazil. Specific offshore extraction technologies have been developed and used in Brazil by Petrobras, the main Brazilian company in petroleum field, for the extraction in the so-called "deep" oil basins in the Atlantic Ocean (ORTIZ NETO and DALLA COSTA, 2007). The extraction, in this condition, is made by means of ships or platforms, where the connections between the basins in the ocean floor and the ships or platforms are done through flexible oil pipes, called risers. Flexible risers are suitable for floating systems because they can withstand significant horizontal and vertical movements (LEFFLER *et al.*, 2011).

One of the main problems of the offshore oil extraction, according to Basso *et al.* (2019) and Santos *et al.* (2019), is the formation of methane hydrates and paraffins, which block the riser flow. Basso *et al.* (2019) and Santos *et al.* (2019) also state that the formation of hydrates and paraffin is due to specific composition of the oil associated to high pressure and low temperature environmental conditions, common in offshore extraction sites. The formation of hydrates and paraffin is a problem that consumes a considerable amount of time from the people in charge of keeping the flow in the oil pipes (LEFFLER *et al.*, 2011), and can stop the extraction in a basin for months, causing significant financial losses (SANTOS *et al.*, 2019).

There are some strategies currently being used to remove hydrates and/or paraffin obstructions in oil pipes, according to Basso *et al.* (2019) and Santos *et al.* (2019). Among the possible cleaning methods, robotic solutions show great potential (BASSO *et al.*, 2019). In-pipe inspection robots are already used by petrochemical, water supply and fluid transport industries (NAYAK and PRADHAN, 2014). Similar systems, dedicated for clearing procedures, are powerful tools for cleaning deep sea risers (MENEZES *et al.*, 2017). Robots are considered safe because they are able to eliminate the necessity of human presence in high-risk environments (PIERES *et al.*, 2017). Some current in-pipe robots operate receiving energy from cables, known as umbilical cables. The distances between the ships or platforms and the basins in deep seas are usually significant, so the risers are usually some kilometers long and present multiple curves, as they are flexible. The long and sinuous path that the umbilical cable shall track inside a typical pipe generates significant friction forces that the robot must overcome. This is one of the most important challenges in the development of in-pipe robots (BASSO *et al.*, 2019).

The Annelida is an in-pipe robot being designed to clean risers with diameters from four to ten inches, with turns of at least five times its diameter. These risers are used in the offshore extraction by Petrobras and may suffer from the obstruction by hydrates and/or paraffins. The current valve development is being performed by the Mechatronics and Control Lab (LAMECC) from the Federal University of Rio Grande do Sul and Petrobras. Annelida uses the combination of two locomotion mechanisms, as defined by Kakogawa and Ma (2010): anchor mechanism and inchworm movement system, resulting in a hybrid solution composed by the two mechanisms. This combination offers good traction in forward movement and the ability to operate in multiple diameters if a suitable change in the legs structure is performed (SANTOS *et al.*, 2019). The robot locomotives operate with two leg groups, each one of them located in each extremity of a main hydraulic linear actuator. This hydraulic actuator is responsible for the inchworm movement of the robot, while the leg groups use secondary smaller actuators to create anchoring contact forces against the internal pipe surfaces. The geometry of the legs and the contacting angles with the walls creates a self-locking behavior (BASSO *et al.*, 2019), where the movement is blocked in one direction allowing the robot to advance. The self-locking behavior indicates that when the dragging friction forces increase, the anchoring forces also increase. In the forward movement, all the secondary actuators of the locomotive expand, contacting the wall, while the rear actuators are released. After the self-locking of the legs, the main actuator moves the robot forward in an inchworm movement. Two locomotives are positioned in the extremities of the robot, allowing it to move in both directions. To move backwards the sequence of actions is the same, only applied to the rear locomotive. A fail-safe behavior is based in a strategy that uses helicoidal springs in the secondary actuators, aiming to guarantee the legs releasing in a system fault. Figure 1 presents a picture of an Annelida prototype, where the leg sets and the main piston are highlighted.
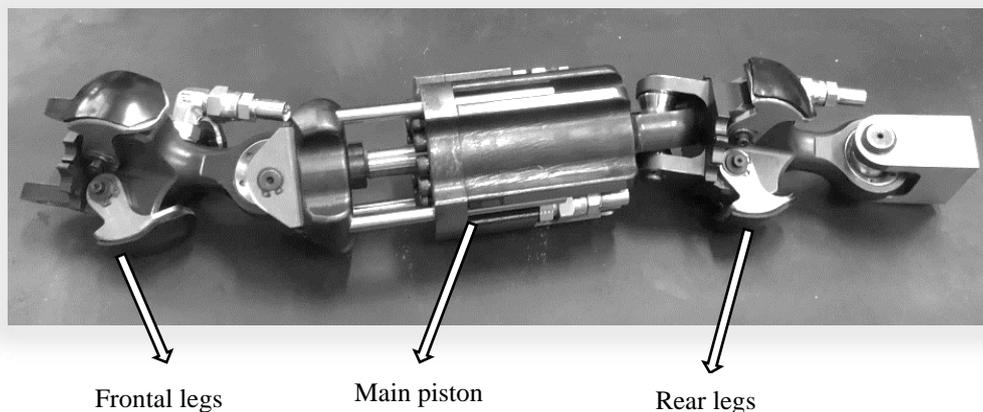

Figure 1. Annelida's locomotive.

The main actuator is a double action cylinder controlled by a solenoid driven compact regenerative hydraulic valve, originally designed by Mendel (2019), which consists of the electromechanical system to be controlled in current research. Therefore, a mathematical model of the mechanical dynamics, including the operation solenoid, is firstly presented. Open loop experimental results, used to evaluate the mathematical model, are presented, together with a description of the experimental rig used for the tests (closed-loop experiments are currently being conducted and are subject of future work).

Further, a feedback linearization strategy is proposed to cancel the nonlinearity of the valve solenoid, resulting in a linear second order system. Then, a sliding mode controller is proposed and applied to the spool valve control. Later, the proposed control scheme is tested in simulation and compared with a traditional sliding mode and a PID controller.

2. MAIN CONCEPTS

This section provides the main concepts applied in the development of this paper.

2.1 The compact hydraulic valve

Mendel (2019) developed a compact regenerative hydraulic spool valve for Annelida's main actuator control and a mathematical model was proposed considering the dynamics of the volumetric flow rate through its orifices. The design was evaluated moving a piston with an external load. The schematic diagram of the designed valve is shown in Figure 2.
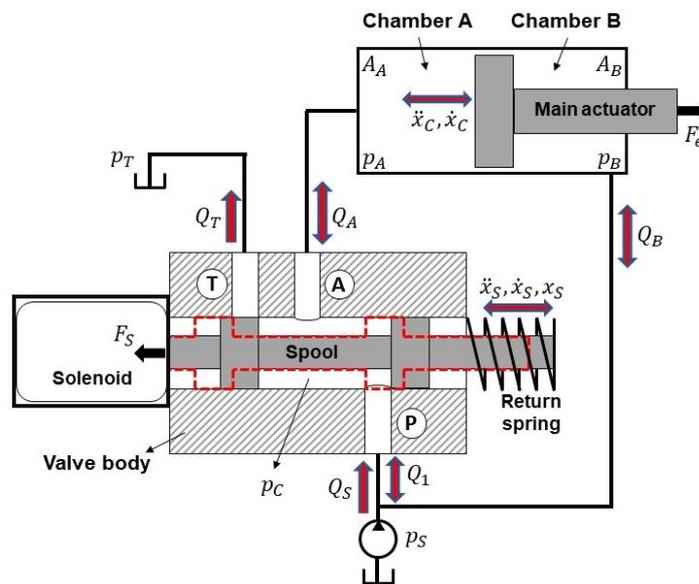

Figure 2. Operation schematic of the designed valve. Adapted from Mendel (2019).

The valve is of the type of sliding spool. For this kind of valve, the components usually are the valve body, control spool, return spring and a solenoid actuator used to drive the control spool inside the valve body. In this configuration, the control spool operates in the same way as a small piston inside the valve body, sliding in a linear guide, opening and closing the body chambers passages and thus changing the oil flow rates directions (MAJUMDAR, 2002). During the sliding motion of the spool, the forces from the return spring, friction and flow rate affect its movement. Also, the nonlinearity of the solenoid difficult its position tracking control. Due to these nonlinearities and intrinsic parameters uncertainties of the system, a sliding mode controller was chosen to control the spool position, as suggested, for example, by Lee *et al*. (2015) and Perondi and Guenther (2000). An important characteristic of this system is that, aiming at developing a compact device due to the small available room inside the ducts, it was proposed the use of only one solenoid actuator to drive the valve spool. This fact results in an asymmetrical actuator system, so that, the valve "opening" movement is performed through the solenoid action, while the "closing" movement is executed by means of the solenoid spring restitution effect. To deal with this characteristic, nonlinear control techniques were considered, and, taking into account the solenoid characteristic behavior, it was proposed applying a linearization approach (state feedback linearization) together with a robust nonlinear technique (slide mode control), seeking to improve the control robustness.

2.2 Feedback linearization

Feedback linearization is a nonlinear control strategy that consists in transforming the nonlinear system into a full or partially linear system, and then use linear control techniques to complete the control model (SLOTINE and LI, 1991). The usual concept of the feedback linearization technique is to choose a control law u that cancels the nonlinearities of the system, leaving a controllable linear system problem (KHALIL, 2002). Feedback linearization can be also used as a model-simplifying technique for robust or adaptative controllers (SLOTINE and LI, 1991), such as a sliding mode controller, as in current approach. Feedback linearization technique was used by Kwon *et al*. (2006) to control a hydraulic servo system and by Seo *et al*. (2007) to control a rotational hydraulic drive, for instance. Both authors successfully controlled nonlinear hydraulic systems using feedback linearization, supporting its well-known control capability

(KWON *et al.*, 2006) and that it is also an appropriate control strategy to be used to improve a standard controller performance, like a PID (proportional + integral + derivative) control scheme (SEO *et al.*, 2007).

2.3 Variable structure control

According to Slotine and Li (1991), nonlinear control strategies can handle a wider range of systems than linear control. Also, some nonlinear strategies can handle intrinsic modelling uncertainties. Variable structure control is a strategy that allows the models to be imprecise, meaning that this controller can withstand uncertainties and eventual changes in the plant parameters (SLOTINE and LI, 1991). The ability of dealing with parameters changes is a characteristic of the so-called robust control. The uncertainties in the modelling of a system, defined by Slotine and Li (1991) can take place in two forms:

- Structured (or parametric) uncertainties: inaccuracies in plant parameters, included in the model.
- Unstructured uncertainties (or unmodeled dynamics) that results in inaccuracies on the system order.

The sliding mode controller is a well-known robust variable structure control method, with successful applications in robotics (SLOTINE and LI, 1991). The controller operation is based on a high frequency switching behavior of the control law, as a function of the system states, near a so-called sliding surface (UTKIN *et al.*, 1999) in the state-space. The state trajectories, given any nonzero initial condition, will be oriented, by effect of the control action, towards the sliding surface, and, once reached it at some finite time t_1, the state remains in the surface, so the state trajectory will belong to the sliding surface for $t > t_1$ (UTKIN *et al.*, 1999), which means the state trajectory will be confined at the vicinity of the sliding surface and will keep switching its direction indefinitely. The sliding surface must be designed in a way that the system dynamics assumes a desired behavior, usually a convergent to zero error trajectory, in a tracking problem, per example. For a second order system, a state-space representation can be given by Eq. (1) and (2),

$$\dot{x}_1 = x_2 \tag{1}$$

and,

$$\dot{x}_2 = h(x) + g(x)u \tag{2}$$

Applying the order reduction property, we can define a first order sliding surface as presented in Eq. (3) (KHALIL, 2002),

$$S(x,t) = cx_1 + x_2 = 0 \tag{3}$$

Despite it is usually denominated as a "surface", due to the generalization for the higher-order cases, this equation represents a line in the phase plane. Once in the surface described by Eq. (3), the movement is governed by Eq. (4),

$$\dot{x}_1 = -cx_1 \tag{4}$$

where, choosing a positive value for c guarantees that $x(t)$ converges to zero and the rate of convergence can be managed by a suitable choice of c (KHALIL, 2002). The value of c can be determined with suitable design specifications. As consequence, the system tracking error, which can be defined as $e = x - x_d$, where x_d is the reference value, can be defined by the choice of the parameter c. The sliding surface can be written as a function of the tracking error, as in Eq. (5) (SLOTINE and LI, 1991),

$$S(x,t) = \dot{e} + ce = 0 \tag{5}$$

Seeking to develop a control law that guarantees the trajectory convergence and the stability condition related to the origin, $S(x,t) = 0$, a proper Lyapunov function with negative first time derivative, along the system trajectory, can be chosen (UTKIN *et al.*, 1999). The control law u must assume $u^+(x,t)$ if $S(x,t) > 0$, and $u^-(x,t)$ if $S(x,t) < 0$ (UTKIN *et al.*, 1999). To achieve this condition, the control law can be written, for instance, as (UTKIN *et al.*, 1999),

$$u(x,t) = -K_s sign(S) \tag{6}$$

where $sign(S)$ is a function that assumes the value of $+1$ if $S > 0$, and -1 if $S \leq 0$. By choosing K_s to be large enough, the trajectory convergence to the reference is guaranteed and the sliding condition is verified (SLOTINE and LI, 1991).

Sliding mode control strategy was adopted by Lee *et al.* (2015), Perondi and Guenther (2000) and Fang *et al.* (2017), for control of pneumatic and hydraulic valves. Lee *et al.* (2015) applied a sliding mode controller in an on/off solenoid operated valve and successfully controlled the spool position of a hydraulic valve. The results indicate that, as expected, the sliding mode controller for a pneumatic valve is more robust to inertial variations than the traditional state feedback

controller (PERONDI and GUENTHER, 2000), and that the sliding mode when applied to hydraulic valves shows best general performance than the standard PID controller (FANG *et al.*, 2017).

2.4 Chattering

Chattering is a phenomenon of finite frequency and amplitude oscillations that appear in many sliding mode implementations (UTKIN *et al.*, 1999). It occurs due to the discontinuous nature of the control law across $S(x, t)$, as the control switching is imperfect (SLOTINE and LI, 1991). Chattering is undesirable, as it involves high control activity and may excite high-frequency dynamics not considered in the system modelling, such as unmodeled structural modes, neglected time-delays, and so on (SLOTINE and LI, 1991). Also, it can cause long term wear damage in mechanical components of the systems.

3. SYSTEM DESCRIPTION AND MODELLING

This section describes the manifold on which the work is developed and presents the modelling of this system.

3.1 Manifold description

In order to enable the realization of the experiments with different control strategies, a prototype valve was built based on the manifold developed by Mendel (2019). This prototype contains only one valve of the manifold, which is the one responsible for controlling the flow rate to the cylinder. Figure 3 presents the diagram of the manifold.
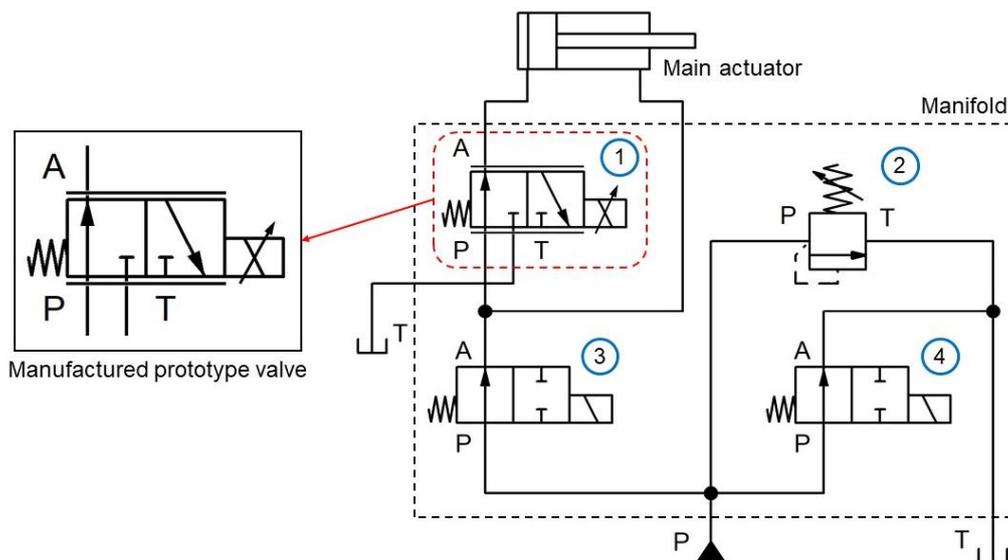

Figure 3. Hydraulic circuit of Annelida's control manifold. Adapted from Mendel (2019).

Figure 3 shows that the manifold contains one valve to control the flow rate to the cylinder (1), one pressure relief valve (2), and two valves to control the flow directions inside the manifold, (3) and (4). The valve built for this experiment is a model of the valve (1) of the manifold, as highlighted in Figure 3.

The mathematical model of the valve was programmed in the Matlab/Simulink system, and evaluated in open loop using experimental data, as presented in the Section 3.4.

3.2 Second order system

The valve is an electromechanical system composed of one valve body, a control spool, a solenoid, and a return spring. The mechanical dynamics can be modeled as a second order system, following Newton's Second Law, as described in Eq. (7),

$$m\ddot{y} + b\dot{y} + ky = F(V, y) \tag{7}$$

where m is the moving mass of the mechanical set composed by the spool, solenoid core and fixation components; b is the viscous damping coefficient due to the friction between the spool with the valve body; k is the spring stiffness constant and $F(V, y)$ is the solenoid force actuating on the valve spool, which depends on the solenoid input voltage V and the

spool position y. The solenoid shows a nonlinear behavior, which means the applied force decreases with the rise of the actuator displacement from the origin. The graph shown in Figure 4(a) represents a typical force output for different power levels related to its behavior with the increase of the displacement.

The selection of the input voltage not only depends on the desired power, but also on the working cycle of the solenoid to avoid overheating. In Figure 4(a), the recommended working cycle for each power level is shown as the percentual active time. Each power level corresponds to a correlated input voltage, analytically estimated, presented in Figure 4(b).

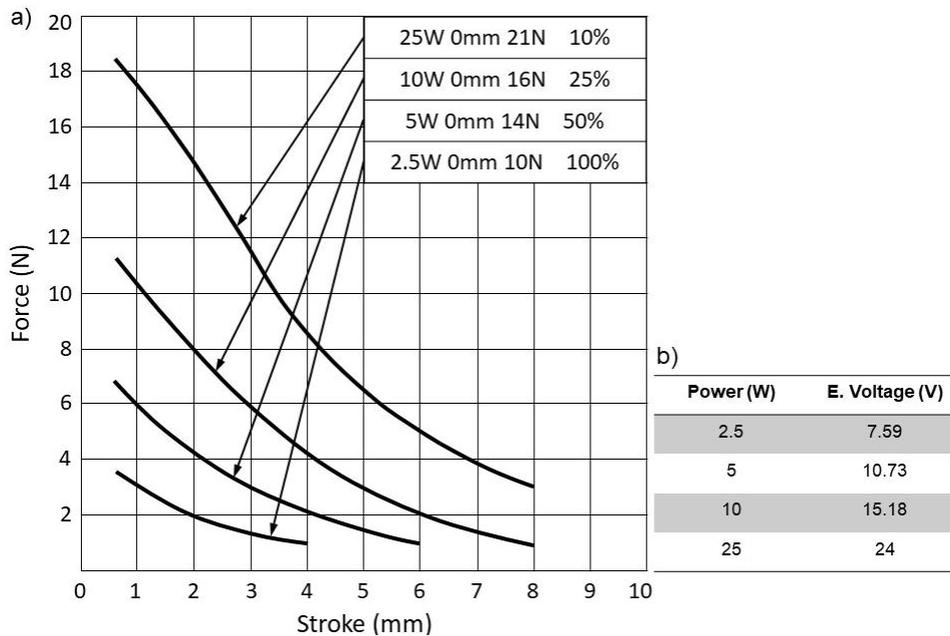| Power (W)	E. Voltage (V)
2.5	7.59
5	10.73
10	15.18
25	24

Figure 4(a). Typical solenoid force output according to its actuator position and available power. Adapted from JF-0826B datasheet; (b) Correspondent solenoid input electric voltage for each power level.

In next section, the experimental rig and the model validation open-loop experiments are presented.

3.3 Experimental system

The experimental rig consists of the valve prototype, with its spool connected to the solenoid. A Hall effect sensor is attached to the valve, to measure the spool position. The solenoid and the sensor are connected to the control hardware, which is connected to a microcomputer. Figure 5(a) illustrates the setup schematic, while Figure 5(b) presents a picture of the rig used in the tests. The solenoid is a JF-0826B model, from the manufacturer Yanke Electric. This model was chosen due to its output force, low cost, and availability in the market. The sensor is a proportional Hall effect sensor, model A1302 from the manufacturer Allegro, that outputs an electric voltage value proportional to the proximity with a magnet. The magnets used are two neodymium class N52, fixed to the spool. The return springs are two of the solenoid built-in ones, placed in parallel to increase the return force, and, to guarantee proper movement of the system mass, ISO VG 68 hydraulic fluid was added into the valve chamber, without extra pressurization. The microcomputer used in the experiments is IBM-PC compatible with an Intel Core i7 with 2.00GHz clock processor, and 16 GB RAM memory.

The control hardware used in the experimental procedures was designed by Teixeira (2020). The system consists of an electronic digital device developed for control of pneumatic servo-actuators based in real-time embedded operational systems, using an ESP32 microcontroller. According to Teixeira (2020), the hardware is composed by a circuit specially designed for conditioning the signals acquired by the sensors. Once these signals are conditioned to adequate electric voltage and current levels, they are sampled and converted from analogic to digital. The digital data is then sent to the microcontroller, which can be coded in C language to generate the control signal, which is sent to a driver that furnishes an adequate electric voltage output level for the solenoid operation. The microcontroller communicates with a microcomputer by Universal Serial Bus (USB) connection. A schematic of the experimental rig is presented in Figure 5(a), while an image of the system in Figure 5(b).

3.4 Experimental open-loop evaluation

Figure 6 shows the open loop experimental results, in comparison with the open loop simulations. The valve was opened and closed (with total stroke of 3mm) with different electric voltage levels applied to the solenoid. The microcontroller was programmed using Arduino IDE software.
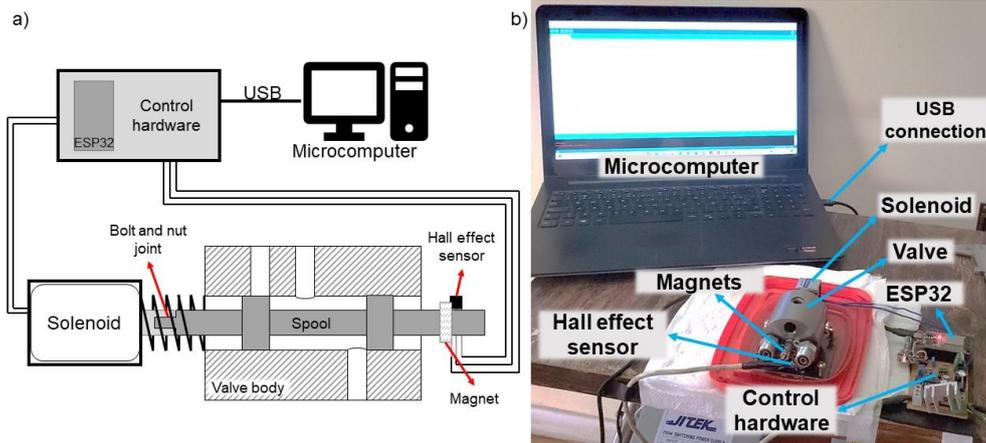
Figure 5(a). Schematic of the experimental setup; 5(b). Experimental setup image.

Before each experiment, the sensor is calibrated by an automatic calibration routine. The signal was filtered in real-time with a low pass IIR digital filter, with 100 Hz cutoff frequency. Results were also filtered in post-processing in Matlab, using a low pass IIR with 100 Hz cutoff frequency. In Figure 6, the experimental trajectory is represented with dashed lines, while the simulated trajectories are represented with solid lines. The forward trajectory of the spool is performed through the solenoid actuation, while its return occurs due to the return spring.
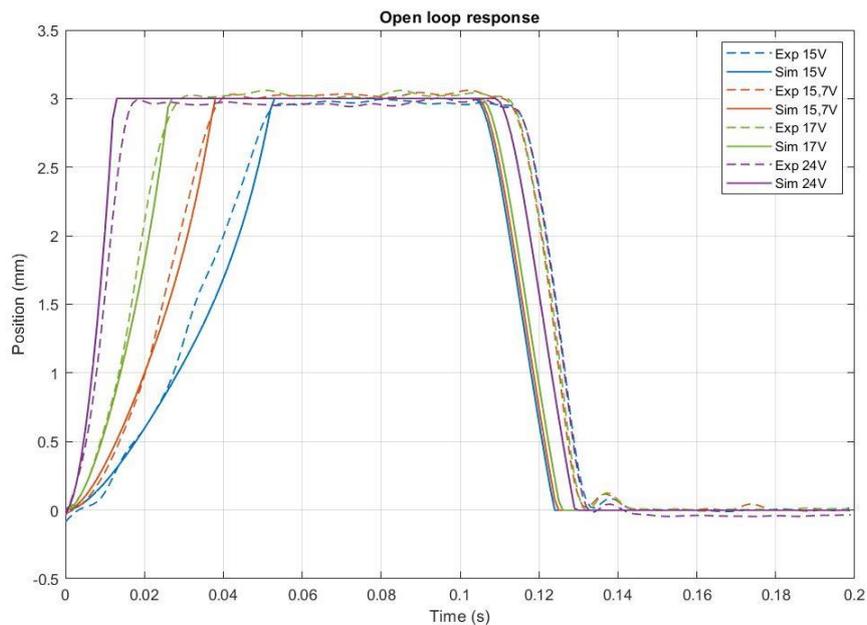

Figure 6. Open loop experimental results.

The simulated trajectories, both in forward and return movement, display similar behavior compared to the experimental ones, in four different voltage levels. The experimental return trajectories present a small delay when compared to the simulated ones, probably due to static friction force between the contact surfaces of the spool and the end stop surface, holding the spool in the stopping position a little longer.

4. CONTROL DESIGN

In order to compensate the solenoid nonlinearity in the control system, a feedback linearization strategy is adopted. The system in Eq. (7) can be rewritten in a closed loop as in Eq. (8),

$$\ddot{y} = -a_1 y - a_2 \dot{y} + a_3 u \tag{8}$$

where $a_1 = -\frac{k}{m}$, $a_2 = -\frac{b}{m}$, $a_3 = \frac{F(V,y)}{m}$, and u is a control signal. A control law is proposed, as shown in Eq. (9), to cancel the nonlinearity $F(V,y)$, as long as $F(V,y) \neq 0$.

$$u = \left(\frac{m}{F(V, y)}\right) v \tag{9}$$

Substituting the control law into Eq. (8), the nonlinear term is cancelled, and the system can be represented in the state-space form, as shown in Eq. (10) and Eq. (11),

$$\dot{x}_1 = x_2, \tag{10}$$

$$\dot{x}_2 = a_1 x_1 + a_2 x_2 + v \tag{11}$$

4.1 Sliding mode controller

Following the sliding mode theory presented in Section 2.3, a control law v for the linearized system is proposed:

$$v = -K_s sign(S) \tag{12}$$

where K_s is a constant value to be determined to achieve trajectory convergence and S is the sliding surface. One of the ways of designing a sliding mode controller, as described by Slotine and Li (1991) and Utkin *et al*. (1999), is to propose a sliding surface according to the desired system, and then find a suitable control law that guarantees convergence.

As already described, for a second order system, the sliding surface must be of first order, so the proposed surface is

$$S(e_1, x_2, t) = -c_1 e_1 + x_2 \tag{13}$$

where the error is given by $e_1 = x_d - x_1$. The proposed sliding surface is similar to those used by Lee *et al*. (2015), and Perondi and Guenther (2000). By using Laplace's transform, a transfer function of the first order sliding surface can be found, as shown in Eq. (14), where the constant value c_1 will be determined to guarantee that x_1 converges to the reference value x_d in finite time (PERONDI and GUENTHER, 2000),

$$\frac{x_1}{x_d} = \frac{c_1}{s + c_1} \tag{14}$$

By the dynamic response of this system, c_1 can be determined by any specified settling time t_a, as shown in Eq. (15), adapted from Franklin *et al*. (2014),

$$t_a = \frac{4.6}{c_1} \tag{15}$$

Next, the controller gain K_s must be determined. Therefore, a value between 0 and 24V (solenoid nominal operating voltage) can be chosen, and then adjusted interactively with the aid of simulation and/or experimental results.

4.2 Chattering solution

To avoid annoying chattering effects, the boundary layer solution (UTKIN *et al*., 1999) was adopted. In this approach, the control law is replaced by a saturation function, which substitutes the function $sign(S)$, with fixed width boundary layer encompassing the surface $S(e_1, x_2, t) = 0$. The width of the boundary layer is determined by a constant ε. If $|S(e_1, x_2, t)| > \varepsilon$, the control law does not change and $sat(S) = sign(S)$. However, when inside the boundary layer, $|S(e_1, x_2, t)| < \varepsilon$, the control law is continuous, and $sat(S) \neq sign(S)$ (UTKIN *et al*., 1999). The proposed saturation function used in the controller is defined by Eq. (16) and Eq. (17),

$$v = -K_s sign(S), \tag{16}$$

for $|S| > \varepsilon$, and

$$v = -\left(\frac{K_s}{\varepsilon}\right) S, \tag{17}$$

for $|S| \leq \varepsilon$. The size of the boundary layer can be determined by analyzing the sliding surface trajectory in simulation, where the maximum absolute values that $S(e_1, x_2, t)$ assume around the origin $S(e_1, x_2, t) = 0$ are observed, and a similar value can be assumed as the value of ε. Then, the value is manually adjusted to fit the trajectory parameters as required by the controller design specifications.

4.3 Control implementation

In closed loop, the model was simulated in Matlab/Simulink system with the proposed FLSM (feedback linearization and sliding mode) controller, a sliding mode and a PID controller. The PID parameters were tuned using Ziegler and Nichols second method, according to Franklin *et al*. (2014). The simulation aimed to emulate the spool controlling the valve flow in two different levels of orifice opening: 1 mm and 2 mm spool stroke. The simulation results and discussions are presented in the next section.

5. RESULTS AND DISCUSSIONS

The spool trajectory results of the controllers simulations are presented in Figure 7.
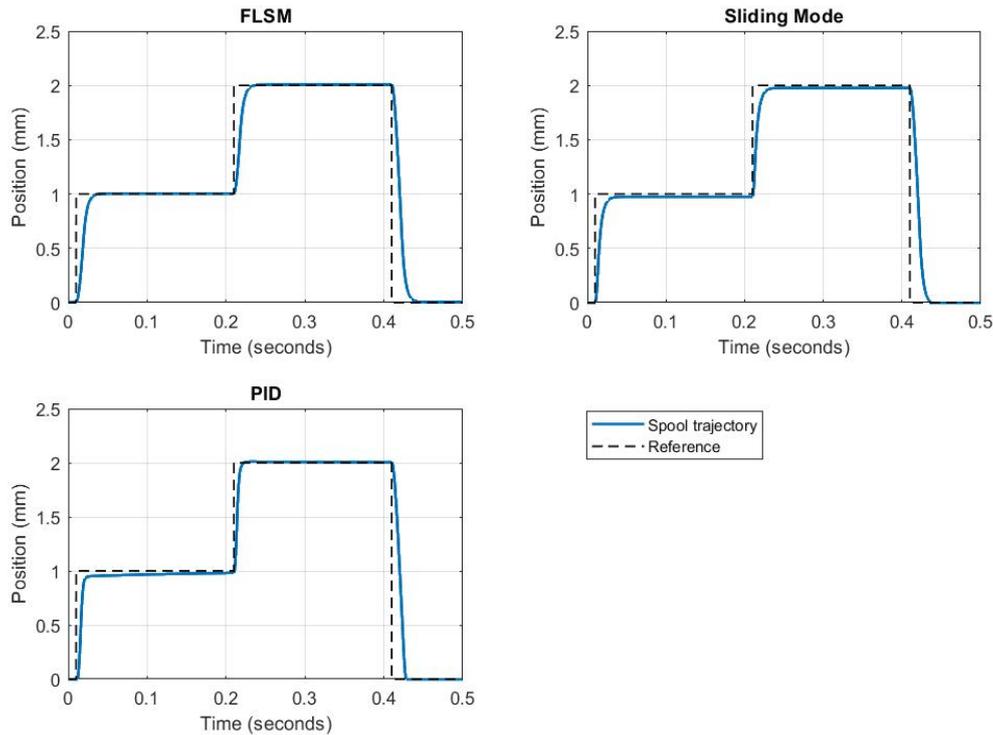

Figure 7. Simulation results.

The PID controller presents an overshoot of about 0.01 mm (0,5%) when the trajectory approaches the reference of 2 mm, then slowly converges, mainly due to the integral action. An increase of the integral gain did not show effective reduction in this value. The sliding mode controller also presents steady-state error of about 0.02 mm (1%), compared to 0.007 mm (0,35%) of the FLSM, from the 2 mm reference, due to the boundary layer solution implemented. The FLSM controller seems to present the best trajectory tracking of the spool, using the same values of K_s, ε and c_1 used in the sliding mode controller. The simulations presented satisfactory results for the FLSM and the standard sliding mode controller, as the spool trajectory converged, and presented a similar performance as of a standard PID controller. By following the presented literature designing procedures, the sliding mode controller design proved to be of a simple execution and great performance, allied to its robustness. The open loop experimental results showed that the proposed valve and solenoid mathematical models corresponds to the valve prototype, displaying similar behavior opening and closing the valve. Thus, the modelled controllers are ready to be implemented in the experimental setup. Future work will address a robustness analysis of the FLSM and sliding mode controller performance regarding parameter uncertainties and the execution of experimental tests with the manufactured proportional valve.

6. CONCLUSIONS

The study performed deals with the precise control of the spool position of a new compact hydraulic proportional valve designed to be applied in the control of the main hydraulic piston of an inchworm type in-pipe clearance robot (the so-called Annelida). As the solenoid used to drive the valve spool is nonlinear, feedback linearization technique was used aiming to cancel its nonlinearity. Then, a sliding mode controller was designed to command the spool trajectory during the opening and closing actions of the proportional valve. The two strategies were combined, resulting in a feedback linearization sliding mode controller, or FLSM. The closed loop system behavior was simulated using the

Matlab/Simulink interface, allowing comparing the FLSM with a standard sliding mode and a PID controllers performance. The proposed FLSM controller presented a good performance controlling the spool position, opening and closing the valve proportionally. Experimental procedures were conducted in open loop, evaluating the mathematical model of the valve used in the simulations. The simulated results are promising, and further experimental studies with the proposed controllers will be carried out in future works.

7. ACKNOWLEDGEMENTS

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9. RESPONSIBILITY NOTICE