A CONTRIBUTION TO RESEARCH INTO THE DESIGN AND ANALYSIS OF A HYDRAULIC ROBOTIC ARM

ALMIR OSMANOVIĆ, ELVEDIN TRAKIĆ, SALKO ČOSIĆ,
MIRZA BEČIROVIĆ
University of Tuzla, Faculty of Tuzla, Tuzla, Bosnia and Herzegovina
almir.osmanovic@untz.ba, elvedin.trakic@untz.ba, salko.cosic@untz.ba,
mirzabecirovic80@gmail.com

Hydraulic robotic arms have a wide range of applications. It utilizes hydraulic power, which involves the use of pressurized fluid to generate and control movements. Hydraulic robotic arms consist of several components, including hydraulic cylinders, pumps, valves, and actuators. The advantage of using hydraulic systems in robotic arms is their ability to generate high forces and torque, enabling the arm to lift heavy loads. Hydraulic systems also provide smooth and precise control over movements, allowing for precise positioning and manipulation of objects. However, hydraulic systems can be more complex and require additional maintenance compared to other types of robotic arm mechanisms. In order to analyze the structural integrity of the hydraulic robotic arm were created a kinematic model. For complemented the design analysis process was created cad model, allowing simulations and analysis of the robot for view the motion of each link and characterize their dynamics.

Keywords:
electro-hydraulic,
robotic,
simulation,
mechatronic,
hydraulic robotic arm

University of Maribor Press

DOI https://doi.org/10.18690/um.fs.5.2023.8
ISBN 978-961-286-781-2

1 Intruduction

Robot is an important element in today's production and assembly. A hydraulic robotic arm is a mechanical device that mimics the movements and functions of a human arm using hydraulic systems. Hydraulic robotic arms have a wide range of applications. They are commonly used in industrial settings for tasks such as heavy lifting, assembling, welding, and material handling. They can also be found in construction equipment. Additionally, hydraulic robotic arms have been used in medical fields for surgical procedures and rehabilitation. A hydraulic robotic arm typically consists of several interconnected segments, often referred to as links or joints. Hydraulic actuators are the key components responsible for moving the joints of the robotic arm. They usually consist of a hydraulic cylinder and motors. Hydraulic fluid is used to transmit force from the actuators to the joints. The movement of the hydraulic robotic arm is controlled by a hydraulic control system. Valves are used to regulate the flow of hydraulic fluid to different actuators, enabling precise control over the arm's movement. To make the robotic arm more intelligent and adaptable, sensors can be integrated into the system. These sensors can provide feedback on the arm's position, force exerted, and other relevant data. This feedback can be used to adjust the arm's movements and ensure accurate and safe operation.

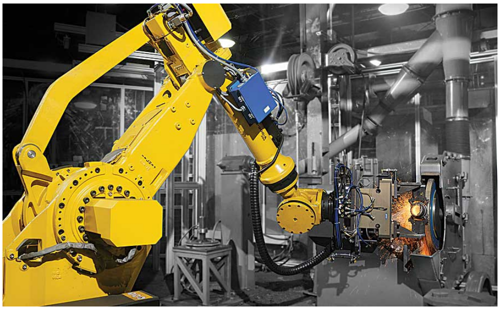

Figure 1: Hydraulic robotic manipulator.
Source: own.

2 Structure of hydraulic robot arm

The structure of a hydraulic robot arm can vary widely depending on its intended purpose and complexity. However, the key components and structure commonly found in hydraulic robots are base, hydraulic elements, sensor and control elements.

The base serves as the foundation of the robot and provides stability and support. It often contains the hydraulic reservoir, pump, and control systems. Depending on the robot's design, it may have multiple joints and segments to enable various degrees of freedom and movements. Hydraulic robots are equipped with end effectors or tools that allow them to interact with their environment. These tools can include grippers, welding torches, cutting tools, or any other devices relevant to the robot's intended tasks. The task of the structure of hydraulic robotic arm is to realize the necessary movement of the robot gripper during the implementation of the work task. This means that it is necessary for the gripper to achieve the planned position and orientation at each point of the path, as well as the appropriate speed and acceleration.

The following figure will show the movement of the hydraulic robot arm when transferring a rectangular object from the stand to the work table. The robotic arm is positioned above the object of manipulation and grasps it with a two-finger gripper.

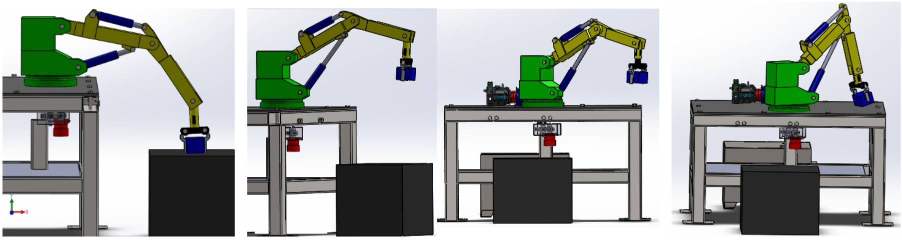

Figure 2: Designed hydraulic robotic arm. Lifting objects and placement object.
Source: own.

3 Components of a robotic arm

The representation of the flow of energy through the hydraulic system of robotic arm is presented in Figure 3. The diagram shows that at the beginning there is a source of mechanical energy, and that finally, the series of energy conversions ends again with mechanical energy (the hydraulic motor or cylinder provides a torque or force that drives the load). Therefore, the hydraulic system has the role of an energy transmitter.

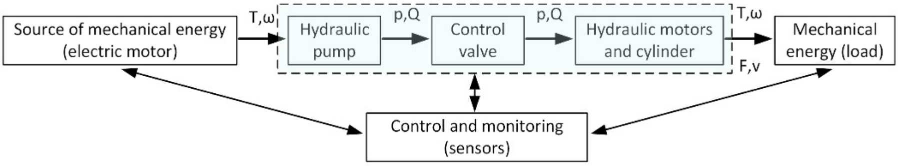

Figure 3: Energy flow through the hydraulic system.
Source: own.

Hydraulic system consists of a hydraulic motor and two hydraulic cylinders. The hydraulic motor has the role of rotating the entire robot. Hydraulic cylinders are used for translational movements of hydraulic arm segments. The cylinder that drives the first segment of the arm has a stroke of 255 mm, and the cylinder that drives the second segment has a stroke of 305 mm. The following figure shows the hydraulic diagram of the entire system with all components. As can be seen, the executive elements of this system are a hydraulic motor and two hydraulic cylinders.

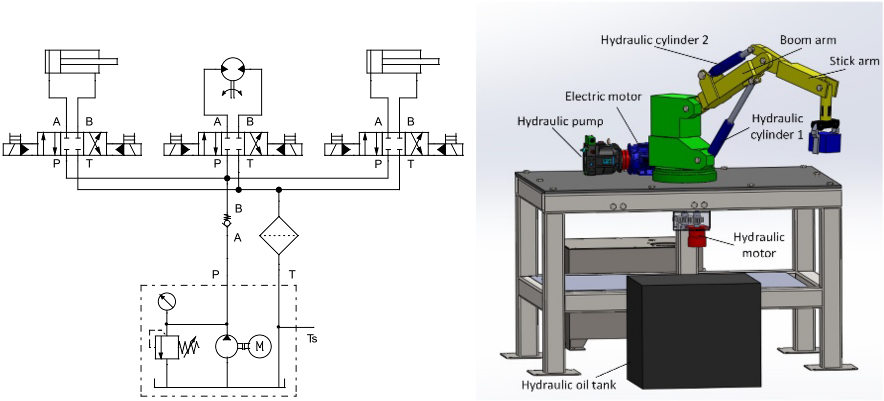

Figure 4: Hydraulic diagram of the robotic arm and main elements.
Source: own.

A hydraulic cylinder is a mechanical actuator that converts hydraulic energy (the pressure of hydraulic fluid) into linear mechanical force and motion. Hydraulic cylinders can be integrated into the joints of robotic arms to provide controlled and powerful movement. They are particularly useful in applications where the robot needs to lift heavy objects, as hydraulic cylinders can generate substantial force while maintaining precise control over the motion. Table 1 shows all the data that will be subsequently used to create the mathematical model.

Table 1: Data for hydraulic cylinders

	Hydraulic cylinder 1	Hydraulic cylinder 2
Piston surface of cylinder	$A_{11} = \frac{D_1^2 . \pi}{4}$ $A_{11} = 1962{,}5\ [\mathrm{mm}^2]$	$A_{12} = \frac{D_1^2 . \pi}{4}$ $A_{12} = 1453{,}8\ [\mathrm{mm}^2]$
Rod surface of cylinder	$A_{21} = \frac{(D_1^2 - d_1^2\ ) \cdot \pi}{4}$ $A_{21} = 945.5\ [\mathrm{mm}^2]$	$A_{22} = \frac{(D_1^2 - d_1^2\ ) \cdot \pi}{4}$ $A_{22} = 945.1\ [\mathrm{mm}^2]$
	Hydraulic system requires a extraction speed v_1=50 [mm/s] for cylinder 1	Hydraulic system requires a extraction speed of v_2=30 [mm/s] for cylinder 2.
Travel time for the total stroke	$v_{i1} = \frac{l_1}{t_1} \rightarrow t_1 = 5{,}1\ [s]$	$v_i = \frac{l_2}{t_2} \rightarrow t_2 = 10{,}1\ [\mathrm{s}]$
Required amount of oil for the given speed	$Q_{c1} = v_{i1} \cdot A_{11}$ $Q_{c1} = 98125 \left[\frac{\mathrm{mm}^3}{\mathrm{s}}\right]$	$Q_{c2} = v_{i2} \cdot A_{12}$ $Q_{c2} = 58830 \left[\frac{\mathrm{mm}^3}{\mathrm{s}}\right]$
Connecting rod retraction speed	$v_{u1} = \frac{Q_{c1}}{A_{21}} = 103.8\ [\mathrm{mm/s}]$	$v_{u2} = \frac{Q_{c2}}{A_{22}} = 62.3\ [\mathrm{o}]$
Selected:	$\emptyset 50/36x255$	$\emptyset 50/36x305$

A hydraulic motor is a mechanical device that converts hydraulic pressure and fluid flow into rotational mechanical power. Hydraulic motors can be integrated into the joints of a hydraulic robot to provide rotational motion. This allows the robot to achieve different degrees of freedom and perform various movements. Hydraulic motors can be used to rotate specific components or manipulators attached to the robot. This rotation can help orient the end effector, tool, or sensor for precise positioning and interaction with the environment. Table 2 shows all the data for hydraulic motor that will be subsequently used to create the mathematical model.

Hydraulic pump creates pressure that drives the hydraulic actuators, such as hydraulic cylinders or hydraulic motors, which move the robotic arm or other components. The pump's flow rate and pressure are carefully controlled to ensure precise and controlled motion of the robotic arm or other parts. This control is essential for accurate positioning, movement, and interaction with the robot's environment.

Table 2: Data for hydraulic motor

Maximum angular speed	$\omega_{Rmax} = 160$ [rad/s]
Max. revolutions of the rotary joint of the robot	$n_{max} = \frac{\omega_{R\,max}}{2\pi} = 25\ [rpm]$
The transmission ratio of the reducer	$i = \frac{n_{M\,max}}{n_{R\,max}} = 20$
Max. revolutions of the hydraulic motor	$n_{Mmax} = i \cdot n_{R\,max} = 500$ [rpm]
Selected hydraulic motor	
Maximum starting pressure	$p_{smax} = 280$ [bar]
Maximum working pressure	$p_{rmax} = 210$ [bar]
Working volume	$V = 16.5$ [cm^3]
Maximum rotation speed	$n = 3000$ [rpm]
The flow required for this hydraulic motor	$Q_M = n_{M\,max} \cdot V = 8.25$ [l/min]

There are different types of hydraulic pumps commonly used in hydraulic robots, including gear pumps, vane pumps, piston pumps, and more.

Table 3: Data for hydraulic pump.

Total flow for all components in the hydraulic system	for cylinder 1: $Q_{c1} = 5.88$ [l/min] for cylinder 2: $Q_{c2} = 3.53$ [l/min] hyd. motor: $Q_m = 8.25$ [l/min] $Q_{max} = Q_{c1} + Q_{c2} + Q_{c3} = 17.66$ [l/min]
Vane hydraulic pump is selected with the following characteristic:	
Maximum pressure	$p_{max} = 137$ [bar]
Maximum flow	$Q_{max} = 30$ [l/min]
Working volume	$V = 16.4$ [cm^3]
Maximum rotation speed	$n_{max} = 1800$ [rpm]
Required rotation speed for this pump	$n = \frac{Q}{V} = 1075$ [rpm]

While hydraulic systems are often associated with hydraulic actuators like cylinders and motors, electric motors are also commonly used in combination with hydraulic systems for different parts of a robot. One common application of electric motors in hydraulic robots is to drive hydraulic pumps. An electric motor can provide the necessary rotational power to drive the pump, pressurize the hydraulic fluid, and initiate movement in the hydraulic system. Electric motors offer precise speed and torque control, which can be advantageous when combined with hydraulic systems. Electric motors can drive hydraulic pumps at varying speeds, allowing for finer control over the hydraulic system's performance. Today, some of the following types of electric motors are most often used in robotics: DC Motors; AC motor; stepper Motors. In this work, an AC asynchronous motor will be used. An AC asynchronous motor, commonly known as an induction motor, is a type of electric motor that operates on alternating current (AC) and is widely used in various industrial and commercial applications due to its simplicity, robustness, and reliability. According to the design task, an alternating three-phase asynchronous cage motor was selected, with power of 7.5 kW, and the speed of the motor is 1440 rpm.

Valves are devices used to control or regulate the start, stop, direction, and flow of pressurized fluid supplied by a hydraulic pump. Distributors and servo valves will be used for this hydraulic system to control and position the executive elements of the hydraulic system. A servovalve is a critical component in a hydraulic system that controls the flow of hydraulic fluid with high precision. Many servovalves operate in a closed-loop system, where feedback sensors provide information about the current position, velocity, or force of the actuator. For this hydraulic system is selected servo valve has the following characteristics: Maximum pressure p_{max} = 315 bar; maximum flow Q_{max}=48 l/min.

Sensors are vital components in hydraulic robots as they provide critical feedback about various parameters, allowing the control system to monitor, adjust, and optimize the robot's performance. Sensors enable the robot to interact with its environment, perform tasks accurately, and ensure safe operation. Robotic system use devices for measuring translational and rotational movements called encoders, then sensors for measuring pressure, as well as a turbine flowmeter.

Finishing devices for a robotic arm refer to tools, attachments, or components that are added to the end effector (gripper or tool) of the robot arm. These devices are designed to perform specific tasks that are often the final steps in a process. The choice of finishing devices depends on the application and industry in which the robotic arm is being used. A gripper is a type of end effector commonly used in robotic arms to grasp, hold, and manipulate objects. Grippers come in different types, each suited for specific applications. Three-Finger Gripper consist of three fingers that move radially to encircle an object. They offer versatility and can grasp a wide range of object shapes and sizes. Two-Finger Grippe, similar to a three-finger gripper, has two fingers that move to grasp an object. It's suitable for tasks where objects have simple shapes and sizes. Vacuum Grippe use suction to hold objects. They are effective for grasping objects with smooth and flat surfaces, such as sheets of material or boxes.

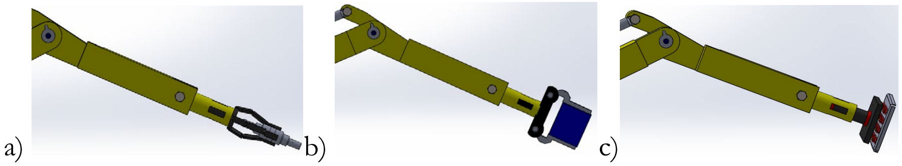

Figure 5: Gripper with two fingers a), three-finger b) and Vacuum gripper c).
Source: own.

4 Modelling of hydraulic robot arm

Hydraulic robotic arm is defined using the hydraulic manipulator equation that includes inertial, gravitational, centrifugal, and external forces acting on the motion dynamics. This model is derived as a function of angles and moments. The base coordinate system $x_0y_0z_0$ is defined in the x_0y_0 plane, which represents the base, and the z_0 axis is the axis around which the robot manipulator rotates. The joint angle q_1 is defined as the angle from the x_0 axis to the x_1 axis around the z_0 axis. At the very end of the reverse joint, the $x_1y_1z_1$ coordinate system is defined, with the axis z_1 around which the joint q_2 rotates. The joint angle q_2 represents the angle from the x_1 axis to the x_2 axis in the direction of the right coordinate system. The coordinate system $x_2y_2z_2$ is attached to the end of arm 1 (boom) (joint q_2), where the joint q_3 rotates around the axis z_2. The joint angle q_3 represents the angle from the x_2 axis to the x_3 axis around the z_2 axis in the direction of the right coordinate system. The $x_3y_3z_3$ coordinate system is attached to the end of arm 2 (stick) (joint q_3) and the direction of the z_3 axis is parallel to the z_2 axis.

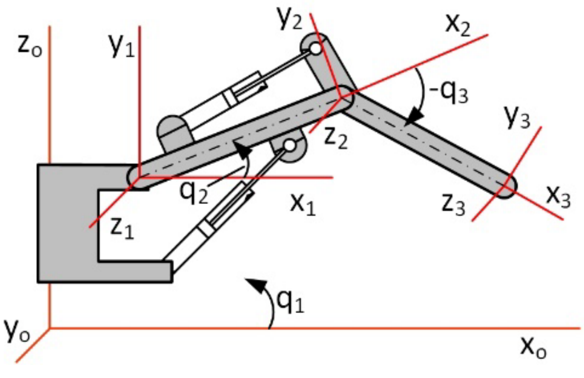

Figure 6: Defining joints and coordinate systems.
Source: own.

Using the joints and coordinate systems defined above, the dynamic equation of the robotic arm is described by the following equation:

$$D\left(q(t)\right)\ddot{q}(t) + h\big(q(t),\dot{q}(t)\big) + c\big(q(t)\big) + B\dot{q}(t) + d(t) = \tau(t) \tag{1}$$

Where is:

$\tau(t)$ - moments generated by hydraulic cylinders;
$D\left(q(t)\right)$ - symmetric inertial n x n matrix;
$h\big(q(t),\dot{q}(t)\big)$ - n x 1 nonlinear vector of Coriolis and centrifugal force;
$c\big(q(t)\big)$ - n x 1 gravitational force vector:
B – diagonal damping matrix;
$d(t)$ – external disturbances involving friction in the joints.

The moments generated by the hydraulic cylinders $\tau(t)$ are a function of the angles of the joints q, while the forces of the hydraulic cylinders F_{opt} act on the joints as a function of the linear displacement of the cylinder $X_{L(i)}$ (t). Moments generated by hydraulic cylinders are related to forces by the following expression:

$$\tau = J \cdot F_{opt} \tag{2}$$

Where J represents the Jacobian matrix that has the following form:

$$J = \begin{bmatrix} \frac{\partial x_{L1}}{\partial q_1} & 0 & 0 \\ 0 & \frac{\partial x_{L2}}{\partial q_2} & 0 \\ 0 & 0 & \frac{\partial x_{L3}}{\partial q_3} \end{bmatrix} \tag{3}$$

$\frac{\partial x_{L1}}{\partial q_1}, \frac{\partial x_{L2}}{\partial q_2}, \frac{\partial x_{L3}}{\partial q_3}$ represent the relationships between the joint angles and the linear displacement of the cylinder. The hydraulic dynamics of each cylinder is defined by the following equations:

$$\frac{V_1}{\beta_e} \cdot \dot{P}_1 = -A_1 \cdot \dot{x} - C_{tm} \cdot (P_1 - P_2) - C_{em1} \cdot (P_1 - P_2) + Q_1 \tag{4}$$

$$\frac{V_2}{\beta_e}\cdot\dot{P}_2 = A_2\cdot\dot{x} + C_{tm}\cdot(P_1 - P_2) - C_{em2}\cdot(P_1 - P_2) - Q_2 \tag{5}$$

$$V_1 = V_{h1} + A_1\cdot x_L \tag{6}$$

$$V_2 = V_{h2} - A_2\cdot x_L \tag{7}$$

Where is:

x_L – displacement of the cylinder;
V_1 - volume of the bore part of cylinder including the volume of the pipe from the valve to the cylinder;
V_{h1} - volume when x_L=0;
V_2 - volume rod part of cylinder piston including the volume of the pipe from the valve to the cylinder;
β_e - modulus of elasticity;
P_1 – cylinder bore surface;
P_2 – cylinder rod surface;
C_{tm} - coefficient of internal oil leakage;
Q_1, Q_2 - flows at the entrance and exit from the cylinder.

The mechanical subsystem model was created in the Matlab-SimMechanics, which is an efficient modelling and simulation tool. This tool uses blocks for modelling bodies and joints with corresponding inputs and outputs where each block defines some physical property such as mass, moment of inertia, possible joint movements, etc. The sensor block provides information about the output movements, while the actuator block defines the inputs. Since the arms of the hydraulic robot are connected to linear hydraulic cylinder, these actuators are modeled as translator joints in the mechanical part of the system.

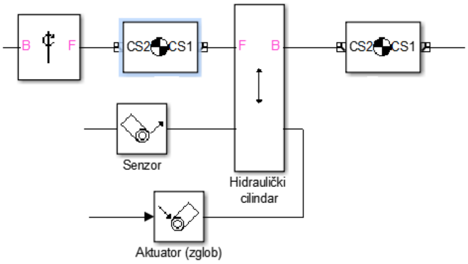

Figure 7: Translator joint of the hydraulic cylinder in the kinematic model.
Source: own.

In order to create a kinematic model of the system, it is necessary to know the masses of the members and the moments of inertia. The following table 4, shows these parameters for hydraulic robotic arm.

Table 4: Masses and moments of inertia of members.

Parameters	**Moment of inertia Ixx $[kg \cdot m^2]$**	**Moment of inertia Iyy $[kg \cdot m^2]$**	**Moment of inertia Ixy $[kg \cdot m^2]$**	**Mass**
Element 1	388.48	1798.10	1991.41	45
Element 2	568.14	515.50	968.33	32

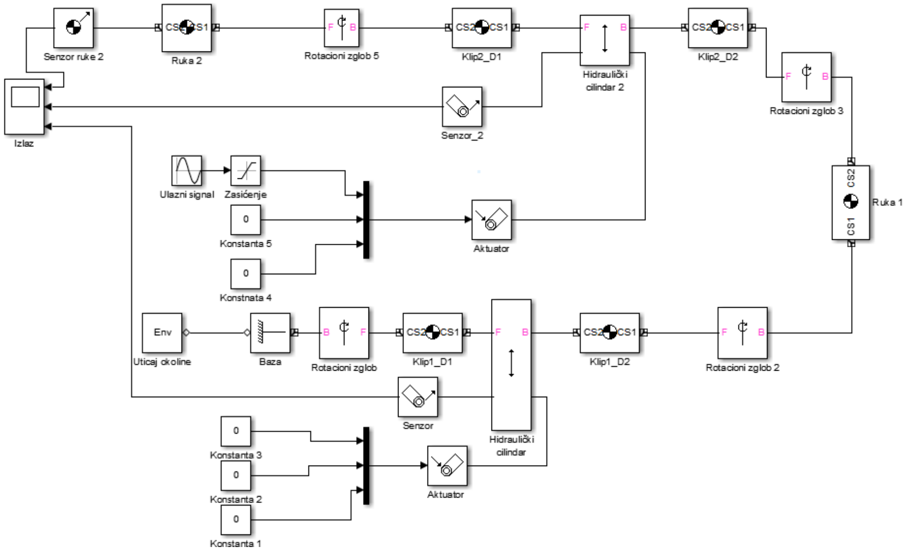

Figure 8: Kinematic model of hydraulic robotic arm.

Source: own.

The Figure 8, show the kinematic model of the hydraulic robotic arm, on which the masses and moments of inertia of the members are defined using the body block, while the hydraulic cylinders are shown using translator (prismatic joints).

The hydraulic subsystem is modelled using the SimHydraulics tool. Hydraulic systems consisting of a hydraulic cylinder controlled by a proportional electric valve. The figure 9, show a hydraulic cylinder modelled in Simhydraulics. It can be noted that the hydraulic cylinder is controlled with 4/3 valve, and with a measuring components.

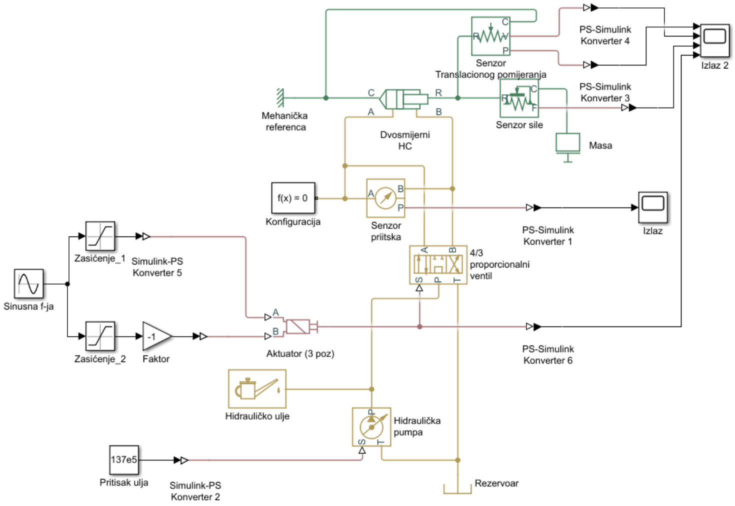

Figure 9: Hydraulic cylinder in Simhydraulics.

Source: own.

In addition to the hydraulic cylinder, the robotic arm also has a hydraulic motor, the model is present on a figure 10.

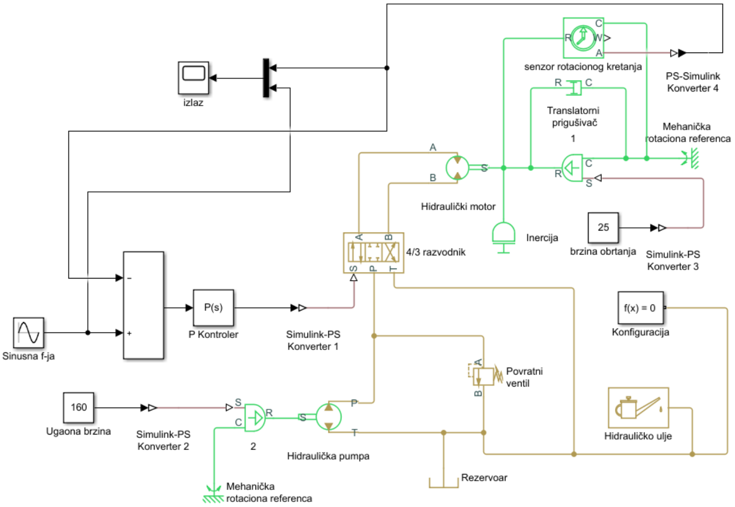

Figure 10: Hydraulic motor in Simhydraulics.

Source: own.

By running the created models in Matlab Simulink, it gets information about the movements of the elements of the hydraulic system. It can also obtain data information according to which the pressures and forces acting on the elements of the system. The following figure shows the diagram of the displacement of the hydraulic cylinder during the movement of the hydraulic robotic arm and hydraulic cylinder pressure change.

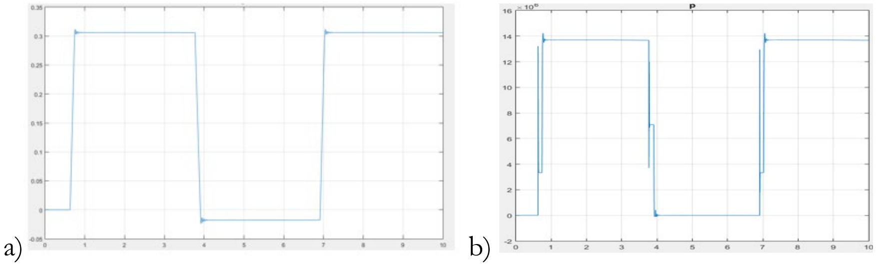

Figure 11: Displacement (a) and hydraulic cylinder pressure change (b).
Source: own.

4 Conclusion

There are many tasks where hydraulic robotic arms have an advantage over classic electric manipulators. Machines in the construction, industry, as well as the control of the movement of heavy loads require high power in relation to weight, rigidity, and short response time, which can be provided by using hydraulic robotic arms. Hydraulic robotic arms (or manipulators) are composed of hydraulic cylinders, hydraulic motors that produce the forces and moments needed to move the joints and are controlled by servo valves, hydraulic pump that provides high fluid pressure in the system, and an electric motor that controls the hydraulic pump. Three types of grippers were designed and presented: gripper with two fingers; three-finger gripper and vacuum gripper. In the end, the components were modelled using Matlab and Cad software, and their movement was simulated. This research presents a simulation model of a mechanism with a hydraulic drive system that performs linear or transversal motion and rotation. The procedure of manual calculation is simplified by creating a simulation model. The provided model gives the force, displacement, velocity, and acceleration of the piston from the hydraulic cylinder. This model-based design is a procedure that allows for the simpler construction of dynamic systems as hydraulic arm robot and the optimization of hydraulic drive systems based on the results of computational modelling.

References

[1] H. Mickoski and M. Djidrov (2019). Modeling of mechanism with linear hydraulic drive system. Mathematical Models in Engineering, Vol. 5, No. 3, pp. 73–78.

[2] A. Osmanović, E. Trakić, S. Čosić, M. Bečirović, (2023): Modeling and simulation hydraulic excavator's arm. XI International Conference "Heavy Machinery-HM 2023", Vrnjačka Banja, 21– 24 June 2023.

[3] A.Osmanović, E. Trakić (2021). Hidraulika. Tuzla: Off-set.
L. Dai, Y. Wu, J. Wang, Y. Gong Li, Y. Liu (2011). Modeling and Control of Flexible Hydraulic Robotic Arm. Advanced Engineering Forum (Volumes 2-3), pp. 334-339

[4] Ziaei K.; Sepehri N. (2000): Modeling and identification of electrohydraulic servos, Mechatronics 10, pp. 761–772.

[5] B. Yao (2004): Programmable valves: A solution to bypass deadband problem of electrohydraulic systems. Proceedings - IEEE International Conference on Robotics and Automation. 4:3459 - 3464 vol.4.

[6] W. Lirong, W. Xiaowang, W. Chenglong, Z. Xin (2010). Mechanical-hydraulic integration modeling and simulation of hydraulic support. International Conference on Computer Application and System Modeling, Taiyuan.

[7] G. R. Reddy (2016). Design and Structural Analysis of a Robotic Arm. Master thesis. Department of Mechanical Engineering, Blekinge Institute of Technology. Karlskrona, Sweden.

[8] A. Akers, M. Gassman, R. Smith (2006). Hydraulic Power System Analysis, Taylor & Francis Group.

[9] Cundiff, J. S. (2002). Fluid power circuits and controls: fundamentals and applications. Boca Raton: CRC Press LLC.

[10] Dieter W., Norbert G., (2008). Hydraulik - Grundlagen, Komponenten, Schaltungen. Springer Verein Deutscher Ingenieure, Berlin.

[11] Blatnický, M., Dižo, J. (2015). Design and analysis of hydraulic arm of light vehicle. In: Zeszyty naukowe Instytutu Pojazdów: mechanika, ekologia, bezpieczeństwo, mechatronika. - ISSN 1642-347X. - 3 (103), s. 5-13.

[12] Xu Jiaqi, Yoon Hwan-Sik (2016). A Review on mechanical and hydraulic system modeling of excavator manipulator system. Journal of Construction Engineering, Vol. 2016, p. 9409370.

[13] K. M. Lynch, F.C. Park (2017). Modern Robotics, Mechanics, Planning and Control, University Printing House, Cambridge, United Kingdom.

[14] Vacca, A., & Franzoni, G. (2021). Hydraulic Fluid Power - Fundamentals, Applications, and Circuit Design. Hoboken, NJ: John Wiley & Sons, Inc.

[15] Marghitu, D. B. (2009). Mechanisms and Robots Analysis with MATLAB. London: Springer-Verlag.