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Design of a Robotic Arm Control System with 06 DOF Applied in Ship Hull Welding by PLC S7.1200

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Abstract— *The paper is about the design of a robotic arm control system with 06 DOF applied in ship hull welding by PLC S7.1200 and HMI teaching arm. The robot is responsible for welding the joints that need to be welded among the hull pieces. On the basis of the theory of solving kinematic problems and dynamic problems (kinetic energy, potential energy, moment of inertia and differential equations of motion), the robot controlling system is designed on Python software and connects with PLC S7-1200 via S7.net virtual library. It helps control the working trajectory through flexible control of 6 motors and control soldering iron Mig to weld the joints at the end of the operation. The control system restores the entire control system for the robotic arm, which can be applied to extend to similar 6 DOS robotic arms as well as directly improve the hull welding productivity in the manufacturing industry with simple operation to help workers completely master the technology.*

Keywords—*Robot arm, robot 6 DOF, controller PLC S7.1200.*

I. INTRODUCTION

In recent years, along with the strong development of electronic technologies, microprocessors, control systems, and computer vision/image processing, the field of robotics has made many breakthroughs and become increasingly popular. Robotic arms can move similarly to human arms or even match the dexterity of human arms. The development of robots has been applied diversely and widely to all fields and industries such as educational robots, nursing robots serving in hospitals, restaurant service robots, advertising robots, household assistants, in factories, workshops, etc. In particular, industrial robotic arms, mechanical devices programmed with functions similar to human arms, are widely used in various fields, such as welding, painting, assembling circuit boards, labeling, material processing support, product testing, and experimentation. Not only do industrial robotic arms possess high flexibility and wide application in many fields, but they also score points thanks to their ability to significantly save space. Now, with the same job, there is no need to use multiple labor sources or heavy machinery anymore. Just one robotic arm is capable of completing these tasks quickly and accurately. Besides, these devices not only save a lot of workspace but also help "expand" the installation space for bulky, complex machinery. With great support from robotic arms, many tasks can be undertaken simultaneously, saving a host of costs such as labor expenses, maintenance and repair costs, and rental expenses. Therefore, researching and mastering the technology of manufacturing industrial robotic arms is an urgent need in Vietnam to approach the fourth industrial revolution. In the field of manufacturing, such as welding, robotic arms play a crucial role in contributing to work efficiency as well as product accuracy and quality

Robot Osacom with the following specifications:
Payload of end-effector: 6kg
Repeatability accuracy: ±0.01mm
Motion control: AC servo motor
Weight of the arm: 130kg
Rotation angle of joint 1: -170° to $+170^\circ$
Upper arm angle of joint 2: -90° to $+150^\circ$
Lower arm angle of joint 3: -80° to $+90^\circ$
Swing angle of joint 4: -180° to $+180^\circ$
Bending angle of joint 5: -140° to $+140^\circ$
Twist angle of joint 6: -185° to $+185^\circ$
Brake: All axes Repeatable accuracy: ±0.01mm
Operating temperature: 0 ~ 45oC

Figure 1: Robot Osacom

II. KINEMATIC ROBOT

A. Problem

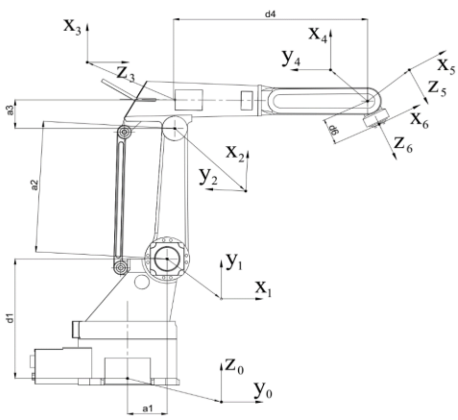

Figure 2: Modeling of robotic coordinate systems

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Table DH :

Joint	$\theta_{i\ (rad)}$	$d_{i\ (m)}$	$a_{i\ (m)}$	$\alpha_{i\ (rad)}$
1	θ_1	d1	a1	$\pi/2$
2	θ_2	0	a2	0
3	θ_3	0	a3	$\pi/2$
4	θ_4	d4	0	$-\pi/2$
5	θ_5	0	0	$\pi/2$
6	θ_6	d6	0	0

Local Denavit matrix:

$$^{i-1}T_{i(qi)} = \begin{bmatrix} \cos\theta i & -\sin\theta i.\cos\alpha i & \sin\theta i.\sin\alpha i & a.\cos\theta i \\ \sin\theta i & \cos\theta i.\cos\alpha i & -\cos\theta i.\sin\alpha i & a.\sin\theta i \\ 0 & \sin\alpha i & \cos\alpha i & d \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

Ta nhận được các ma trận truyền biến đổi tọa độ $^{i-1}A_i$:

Đặt: $c_i = \cos(\theta_i), s_i = \sin(\theta_i)$ và

$c_{ij} = \cos(\theta_i + \theta_j), s_{ij} = \sin(\theta_i + \theta_j)$

a1=0.14 (m), d1= 0.405 (m), a2= 0.5 (m)
a3=0.105 (m), d4=0.7(m), d6= 0.075 (m)

$$^0A_1 = \begin{bmatrix} c_1 & 0 & s_1 & a1c_1 \\ s_1 & 0 & -c_1 & a1s_1 \\ 0 & 1 & 0 & d1 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$^1A_2 = \begin{bmatrix} c_2 & -s_2 & 0 & a2c_2 \\ s_2 & c_2 & 0 & a2s_2 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$^2A_3 = \begin{bmatrix} c_3 & 0 & s_3 & a3c_3 \\ s_3 & 0 & -c_3 & a3s_3 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$^3A_4 = \begin{bmatrix} c_4 & 0 & -s_4 & 0 \\ s_4 & 0 & c_4 & 0 \\ 0 & -1 & 0 & d4 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$^4A_5 = \begin{bmatrix} c_5 & 0 & s_5 & 0 \\ s_5 & 0 & -c_5 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$^5A_6 = \begin{bmatrix} c_6 & -s_6 & 0 & 0 \\ s_6 & c_6 & 0 & 0 \\ 0 & 0 & 1 & d6 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

Ma trận truyền biến đổi tọa độ thuần nhất của khâu cuối là:

$$^0A_6(q) = {}^0A_1\,{}^1A_2\,{}^2A_3\,{}^3A_4\,{}^4A_5\,{}^5A_6 = {}^0A_3\,{}^3A_6$$

$^0A_6(1,1) = A11 = c_1c_{23}(c_4c_5c_6 - s_4s_6) - c_1s_{23}s_5c_6 + s_1(s_4c_5c_6 + c_4s_6)$

$^0A_6(2,1) = A21 = s_1c_{23}(c_4c_5c_6 - s_4s_6) - c_1(s_4c_5c_6 + c_4s_6) - s_1s_{23}s_5c_6$

$^0A_6(3,1) = A31 = s_{23}(c_4c_5c_6 - s_4s_6) + c_{23}s_5c_6$

$^0A_6(4,1) = A41 = 0$

$^0A_6(1,2) = A12 = c_1c_{23}(-c_4c_5s_6 - s_4c_6) + s_1(-s_4c_5s_6 + c_4c_6) + c_1s_{23}s_5s_6$

$^0A_6(2,2) = A22 = s_1c_{23}(-c_4c_5s_6 - s_4c_6) - c_1(-s_4c_5s_6 + c_4c_6) + s_1s_{23}s_5s_6$

$^0A_6(3,2) = A32 = s_{23}(-c_4c_5s_6 - s_4c_6) - c_{23}s_5s_6$

$^0A_6(4,2) = A42 = 0$

$^0A_6(1,3) = A13 = c_1c_{23}c_4s_5 + s_1s_4s_5 + c_1s_{23}c_5$

$^0A_6(2,3) = A23 = s_1c_{23}c_4s_5 - c_1s_4s_5 + s_1s_{23}c_5$

$^0A_6(3,3) = A33 = s_{23}c_4s_5 - c_{23}c_5$

$^0A_6(4,3) = A43 = 0$

- The position of the end effector point E

$$\begin{cases} x_E = A14 \\ y_E = A24 \\ z_E = A34 \end{cases}$$

- The direction of the end effector operation E:

$$\begin{cases} \sin\beta = A13 \\ \cos\beta = \pm\sqrt{1-\sin^2\beta} \\ \sin\alpha = -\dfrac{A23}{\cos\beta} \\ \cos\alpha = \dfrac{A33}{\cos\beta} \\ \sin\eta = -\dfrac{A12}{\cos\beta} \\ \cos\eta = \dfrac{A11}{\cos\beta} \end{cases}$$

B. Reverse problem

$$^0A_1\,{}^1A_2\,{}^2A_3\,{}^3A_4\,{}^4A_5\,{}^5A_6 = T_6$$

Với:

$$^0A_6(t) = T_6 = \begin{bmatrix} n_x & o_x & a_x & p_x \\ n_y & o_y & a_y & p_y \\ n_z & o_z & a_z & p_z \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

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Trong đó: $R^* = \begin{bmatrix} n_x & o_x & a_x \\ n_y & o_y & a_y \\ n_z & o_z & a_z \end{bmatrix}$ là ma trận chỉ hướng của điểm tác động cuối.

$r^* = \begin{bmatrix} p_x & p_y & p_z \end{bmatrix}^T$ là ma trận vị trí của điểm tác động cuối.

$$T_6 = {}^0A_1\,{}^1A_2\,{}^2A_3T(z_3,d_4)$$
$$\times R(z_3,\theta_4)R(x_4,\alpha_4)R(z_4,\theta_5)R(x_5,\alpha_5)R(z_5,\theta_6)T(z_6,d_6)$$

$$\theta_1 = a\tan 2(p_y - a_y d_6, p_x - a_x d_6)$$

$$\theta_2 = a\tan 2(s(\theta_2+\phi), c(\theta_2+\phi)) - a\tan 2(H,D)$$

$$\theta_3 = \theta_{23} - \theta_2$$

$$\theta_5 = \begin{bmatrix} \theta_5^{(1)} = a\tan 2(\sqrt{R_{13}^2 + R_{23}^2}, R_{33}) \\ \theta_5^{(2)} = a\tan 2(-\sqrt{R_{13}^2 + R_{23}^2}, R_{33}) \end{bmatrix}$$

$$\theta_6 = a\tan 2(R_{12}, R_{22}) + \theta_4$$

III. KINEMATIC ROBOT

We have a mathematical robotic model:

$$M(q)\ddot{q} + C(q,\dot{q})\dot{q} + G(q) = \tau$$

$M(q)$: Matrix of mass

$C(q,\dot{q})\dot{q}$: The matrix of the extrapolation forces of inertial forces and centrifugal forces.

$G(q)$: The gravity component vector.

τ : Drive force.

Q :Coordinates system.

- Robot kinematic parameters
- The dynamic parameters of the joints are not known, so we estimate the parameters of each joint through practical measurements. From there, specialized software such as Solidwork, Catia, Inventor are used to build a 3D model for each joint of the robot... to estimate the parameters of each joint.
- Step 1: Calculate the transmission matrices:
- Step 2: Calculate the Jacobi matrices and .
- Step 3: Calculate the mass matrix.
- Step 4: Calculate the matrices of Coriolis and centrifugal inertial forces.
- Step 5: Calculate the matrices of non-conservative forces:
- Step 6: Calculate the drive force/momentum."

IV. VIRTUAL PHYSICAL MODEL FOR A ROBOT ARM BASED ON MATLAB/SIMCAPE MULTIBODY

In reality, when constructing a control problem, it is not guaranteed that the mathematical model describing the system will be 100% accurate. Therefore, after the calculation and construction of the mathematical model, it is necessary to simulate the control system. This is crucial before applying the controller to the real object. From the simulation results, we can evaluate whether the mathematical model is suitable or not, and then propose improvement and modification plans to meet the requirements. Simscape Multibody provides a 3D simulation environment for multi-component mechanical systems such as robot arms, multi-link systems, etc. Simscape Multibody provides representative blocks for links, joints, sensors, moment and force components, etc. Each geometric structure of a link can be drawn by simple blocks in Simscape Multibody. From there, the components of the robot will be assembled and connected in the virtual physical model environment of the robot, with characteristics and responses similar to the real robot. In addition, we can use CAD software to design components such as Autodesk Inventor, and MATLAB/Simscape Multibody can use these CAD files to create system models. Regenerate response

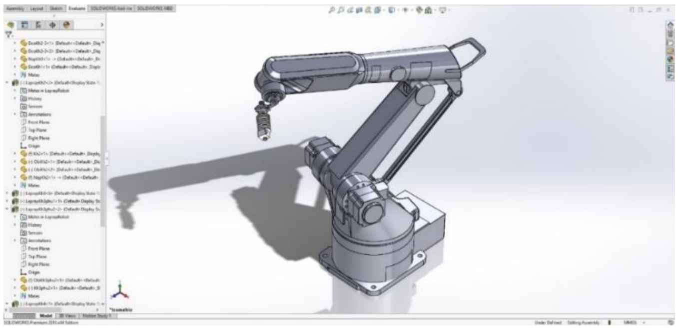

Figure 3: Simscape Multibody on Matlab Simulink

Importing the file.xml into MATLAB, the software will automatically generate a corresponding physical network for the robot model. By adjusting this physical network, we can obtain a virtual physical model for the robot, which can be used for simulation purposes.

V. SYSTEM OF CONTROLLER

Applying the reverse kinematic controlling method to control the robot when we know all about the dynamic quantities in the robot's differential equation of motion. Here we choose the control rule system of the form:

$$u = M(q) + (q, q) + G(q) + Q$$

Controlling 6DOF robot arm trajectory according to the method of controlling the space motion trajectory.

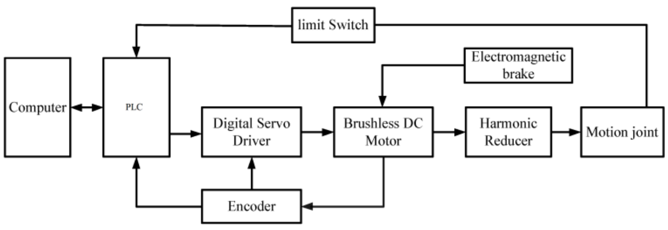

Figure 4: Control diagram in matching space.

The control system consists of a computer (PC) that stores control programs. The control program is executed on the system interface designed on the Visuastudio C# platform. The control signals from the control software interface are sent to the virtual server S7.net. The data from the S7.net server is sent down to two S7-1200 PLCs through Ethernet cables. The PLCs are connected to six servo motor drivers through PULS- (pulse output) and DIR- (direction output) pins. The drivers supply

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power and signals to control the motors through N wires, and receive feedback signals from the motors through encoder cables. The drivers and PLCs are powered by a 24V power supply converter. The PULS+ and DIR+ pins are connected to the positive power supply. In addition, the input of the first PLC is connected to two buttons, a Start button (to start the program), a Stop button (to stop the program in case of emergencies), and a limit switch attached to stage 1. A solenoid valve is used to control the gas supply during the working process. The robot control diagram is shown in Figure 4. The input data is the trajectory of the points that the robot needs to move through. The kinematics block calculates the joint coordinates. The results are sent to the kinematics verification block (which includes conditions about the working space, limits of the working surface, and the robot's motion trajectory). If the results are incorrect, the data is sent back to the kinematics block for reprocessing. If the results are correct, the joint variables are used to calculate the control force through the dynamic processing block. After calculating the dynamic force, the results are sent to the verification block. If the control force meets the conditions, the data is sent to the PLC processor through the virtual server S7.net. If the control force is incorrect, the results are sent back to the dynamic processing block for optimization. When the data is sent to the PLC processor, the signal is transmitted to the executing unit to perform the assigned task. If the task is completed, the process ends. If the task is not completed, a signal is sent back to the PLC processor to continue performing the task until it is completed.

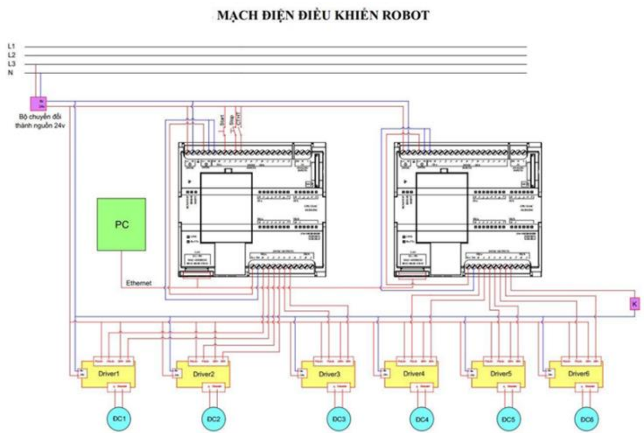

Figure 5: Controlling principle diagram

VI. CONCLUSION

The simulation results show that the control program operates in the workspace trajectory, ensuring the necessary operating positions of the end-effector. Boundary conditions are applied to the control problem, limiting the workspace and incorporating force factors to ensure the direction and position of the end-effector.

The study involves theoretical calculations of the kinematics, dynamics, and differential equations of motion to compute the motion trajectory and work of a 6DOF robotic arm. Based on control theory, a control system for the 6DOF robot is built with 6 motors controlled simultaneously in joint space. The research paper focuses on the design of the complex-shaped welding 6DOF robot control system. The control system is designed using C# software on a PC, which sends signals to the PLC and controls the robot. The successful practical results of the research will be applied to industrial robot teaching and research. The research solution combines simulation and experimental results to optimize the control problem and improve trajectory tracking performance. This approach will be pursued and developed further in future research directions.

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