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Research On Designing Workpiece Loading Robot for High Frequency Induction Heating Machine in Production Facilities in Vietnam

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ABSTRACT
This paper presents a part of the results of research on designing and building a workpiece loading robot for the high-frequency induction heating machine in the production facilities in Vietnam. The robot is used to load 12-kilogram cylindrical steel workpieces, the working length of its arm is 500 mm with an accuracy of ± 1 mm. The robot is designed in 3D based on kinematic analysis and tested for operation in a real production condition. The study is conducted in order to automate the heating-steel process, improving productivity and reducing manpower in the production facilities in Vietnam.
Keywords: Workpiece loading robot, production automation, high-frequency induction heating machine.

I. INTRODUCTION

In heavy industry, the production facilities/companies use robots with various axis configurations with different degrees of freedom, depending on workpieces. The higher this number of degrees of freedom is, the more flexible the robots perform in three-dimensional space. Thus, in order for the robot, which has the high degrees of freedom, to load with the heavy workpiece, its size should be correspondingly large, beside the requirement of high-accurate robot building, leading to an increase in designing and manufacturing costs. At the moment, outstanding robot manufacturers such as Kuka, Stäubli, ABB, Kawasaki... provide a variety of 6-axis robots that are widely used in industrial production such as assembly, metalworking, welding... and have accuracy in the range from 0.02 to 0.1 mm depending on the needs of use [1-4]. However, their cost is greatly high, not suitable for the economic or operating conditions of production facilities/companies in Vietnam. For these reasons, this study is carried out to design and build a workpiece loading robot for the high frequency induction heating machine that can conduct the required operation, being appropriate with a heavy workpiece, having the smallest degrees of freedom, building cost to be smallest and also being convenient to operate and manipulate. This research is necessary and practical in the production conditions of the production facilities in Vietnam and some developing countries nowadays.

II. ROBOT ARM DESIGN

A. Workpiece specifications and induction heating machine layout diagram

The specifications of the workpiece and induction heating machine are shown in Figures 1 and 2. The cylindrical workpiece weighs nearly 12 kg and is made of C45 steel. The workpiece is placed on the feeder next to the heating machine and fed to the machine at a height of 650 mm and 400 mm from the machine door. The feeder feeds up to 20 workpieces in a single feed.

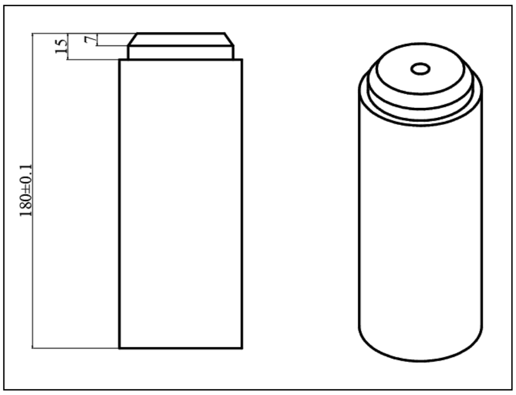

Figure 1. Workpiece size

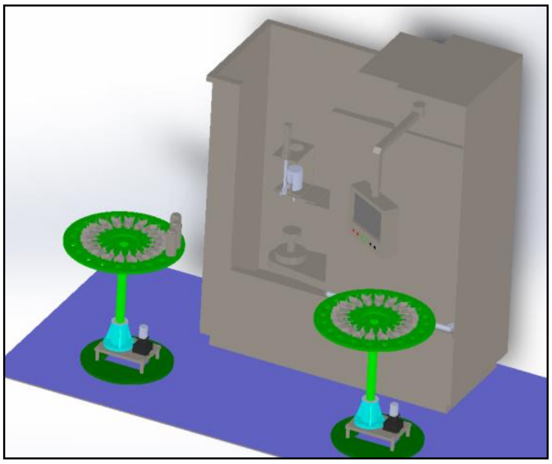

Figure 2. Induction heating machine layout diagram

B. Robot structure design

Technical requirements of the operation: In order for feeding the workpiece described in Figure 2, the robot performs the task of picking up the workpiece from the feeder table and placing it in the machine while the workpiece and the position of the workpiece in the machine are vertical.

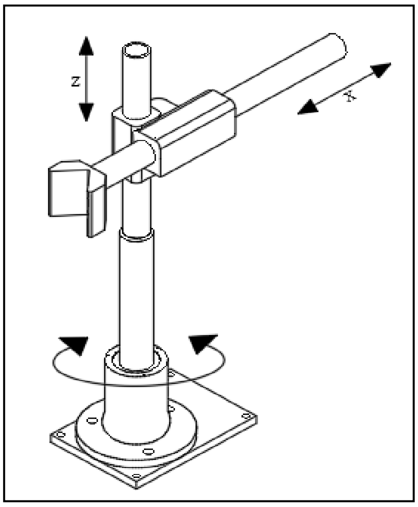

Figure 3. Robot structure

The robot arm is designed with 03 degrees of freedom (one joint for rotation, two joints for motion), described in 3D structure and design as shown in Figure 3.

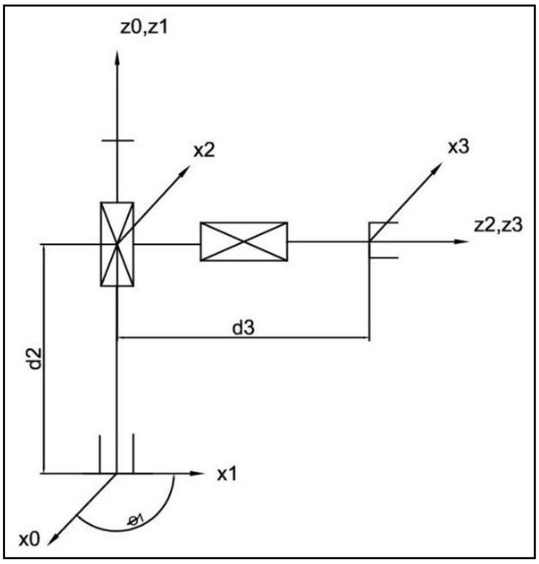

Figure 4. Robot's D-H coordinate system

C. Calculation robot's forward kinematics

The forward kinematics problem for the robot is presented by the Denavit – Hartenberg (D-H) method [5-13]. This study built D-H coordinate system according to figure 4 and:

The position of the coordinate system of joint $(Oxyz)_i$ from the coordinate system of joint $(Oxyz)_{i-1}$ is determined by four D-H parameters θ_i, d_i, a_i, α_i, where:

- θ_i is the angle of rotation around the axis z_{i-1} so that the axis x_{i-1} coincides with the axis x'_i (x'_i // x_i)
- d_i is the distance between common perpendiculars of x_{i-1} and x_i with z_{i-1}
- a_i is the distance between the axis z_{i-1} và z_i
- α_i is the angle of rotation around the axis x_i so that the axis z'_{i-1} (z'_{i-1} // z_{i-1}) coincides with the axis z_i

As a result, the study has the D-H parameters as shown in Table 1 from the coordinate systems above.

TABLE I

DENAVIT – HARTENBERG PARAMETERS

Joint	θ_i	d_i	a_i	α_i
1	θ_1	0	0	0
2	90°	d_2	0	90°
3	0	d_3	0	0

+ The matrix to convert the coordinate system $(Oxyz)_{i-1}$ to the coordinate system $(Oxyz)_i$ as ${}^{i-1}A_i$ is of the form [7]:

$$^{i-1}A_i = \begin{bmatrix} \cos\theta_i & -\cos\alpha_i \sin\theta_i & \sin\alpha_i \sin\theta_i & a_i \cos\theta_i \\ \sin\theta_i & \cos\alpha_i \cos\theta_i & -\sin\alpha_i \cos\theta_i & a_i \sin\theta_i \\ 0 & \sin\alpha_i & \cos\alpha_i & d_i \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (1)$$

+ The matrix ${}^0A_n$ indicates the position of the end effector E and the direction of the manipulation with the fixed frame of reference $(Oxyz)_0$. The matrix ${}^0A_n$ is defined as:

$$^0A_n = {}^0A_1 . {}^1A_2 \ldots {}^{n-1}A_n = \begin{bmatrix} {}^0R_n & r_E \\ 0^T & 1 \end{bmatrix} \quad (2)$$

According to formula (1), the D-H transformation matrices between the coordinate axes are as follows:

$$^0A_1 = \begin{bmatrix} \cos\theta_1 & -\sin\theta_1 & 0 & 0 \\ \sin\theta_1 & \cos\theta_1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (3)$$

$$^1A_2 = \begin{bmatrix} 0 & 0 & 1 & 0 \\ 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & d_2 \\ 0 & 0 & 0 & 1 \end{bmatrix}; \quad (4)$$

$$^2A_3 = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & d_3 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (5)$$

$$^0A_2 = {}^0A_1 . {}^1A_2 = \begin{bmatrix} -\sin\theta_1 & 0 & \cos\theta_1 & 0 \\ \cos\theta_1 & 0 & \sin\theta_1 & 0 \\ 0 & 1 & 0 & d_2 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (6)$$

$$^0A_3 = {}^0A_2 . {}^2A_3 = \begin{bmatrix} -\sin\theta_1 & 0 & \cos\theta_1 & d_3\cos\theta_1 \\ \cos\theta_1 & 0 & \sin\theta_1 & d_3\sin\theta_1 \\ 0 & 1 & 0 & d_2 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

(7)

According to (2)

$$\Rightarrow r_E = \begin{bmatrix} x_E \\ y_E \\ z_E \end{bmatrix} = \begin{bmatrix} d_3\cos\theta_1 \\ d_3\sin\theta_1 \\ d_2 \end{bmatrix} \quad (8)$$

$$\Rightarrow {}^0R_3 = \begin{bmatrix} -\sin\theta_1 & 0 & \cos\theta_1 \\ \cos\theta_1 & 0 & \sin\theta_1 \\ 0 & 1 & 0 \end{bmatrix} \quad (9)$$

+ Velocity and acceleration of the end arm tooling E:

$$v_E = \dot{r}_E = \begin{bmatrix} \dot{d}_3\cos\theta_1 - d_3\sin\theta_1\,\dot{\theta}_1 \\ \dot{d}_3\sin\theta_1 + d_3\cos\theta_1\dot{\theta}_1 \\ \dot{d}_2 \end{bmatrix} \quad (10)$$

$$a_E = \dot{v}_E = \ddot{r}_E = \begin{bmatrix} \ddot{d}_3\cos\theta_1 - 2\dot{d}_3\sin\theta_1\,\dot{\theta}_1 - d_3\cos\theta_1\dot{\theta}_1^2 - d_3\sin\theta_1\,\ddot{\theta}_1 \\ \ddot{d}_3\sin\theta_1 + 2\dot{d}_3\cos\theta_1\dot{\theta}_1 - d_3\cos\theta_1\dot{\theta}_1^2 + d_3\cos\theta_1\ddot{\theta}_1 \\ \ddot{d}_2 \end{bmatrix}$$

D. Calculation robot's inverse kinematics

The task of the inverse kinematics problem is to find the variables that match the coordinates and direction of the defined manipulation.

- Based on (8): $\begin{cases} x_E = d_3\cos\theta_1 & (*) \\ y_E = d_3\sin\theta_1 & (**) \\ z_E = d_2 \end{cases}$
- Achieved $(*)^2 + (**)^2 \Leftrightarrow x_E^2 + y_E^2 = d_3^2({\cos\theta_1}^2 + {\sin\theta_1}^2) \Leftrightarrow x_E^2 + y_E^2 = d_3^2$ Then:

$$\begin{cases} \cos\theta_1 = \pm\sqrt{\dfrac{x_E^2}{x_E^2+y_E^2}} \\ \sin\theta_1 = \pm\sqrt{\dfrac{y_E^2}{x_E^2+y_E^2}} \end{cases}$$

$$\Leftrightarrow \theta_1 = \mathrm{a}\tan 2\,(\sin\theta_1, \cos\theta_1)$$

- Finally:

$$\begin{cases} \theta_1 = \mathrm{a}\tan 2\,(\sin\theta_1, \cos\theta_1) \\ d_2 = z_E \\ d_3 = \pm\sqrt{x_E^2+y_E^2} \end{cases}$$

III. DESIGNING IN 3D AND BUILDING ROBOT ASSEMBLY DRAWINGS

On the basis of the robot kinematics parameters, the 3D design and detailed drawings are built, then the robot arm is fabricated and assembled. In which, the gripper arm is calculated and designed using an electromagnet to clamp the workpiece provided that it can clamp the workpiece with a weight of 12 kg (safety factor is 1.5). Figure 5 is a drawing of the robot arm and a 3D drawing of the entire robot is shown in figure 6. The specifications of the robot are as follows:

- Size:1217 × 410 × 250 mm
- Maximum angle of rotation: 360°
- Movement distance of gripper arm: 500 mm
- The maximum weight of the cylindrical workpiece to be picked up is 12 kg

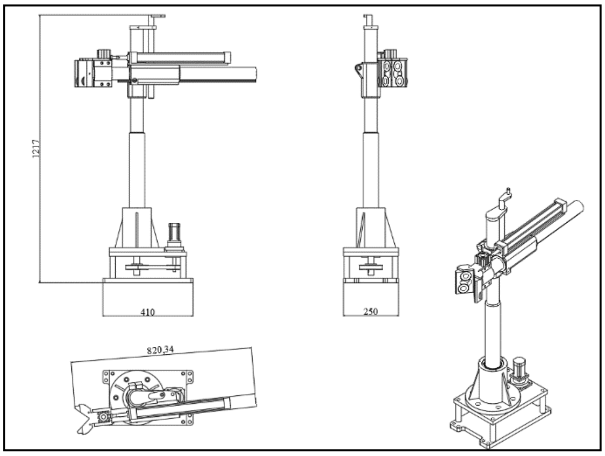

Figure 5. Robot arm assembly drawing

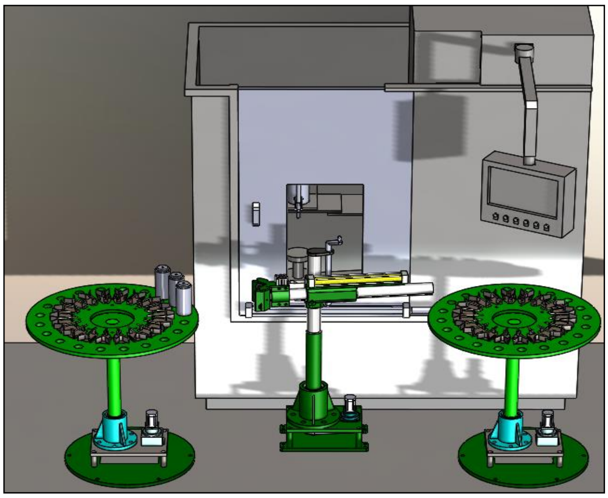

Figure 6. Robot 3D drawing

IV. RESULTS OF BUILDING AND TESTING ROBOT

Based on the assembly and detailed drawings, the robot is fabricated, assembled and tested, then the design of the robot arm is evaluated. For examination, the researcher connected the robot to a control system with a program programmed by PLC (the control system is not presented in this paper). The results show that the robot worked stably and met the requirements and objectives set forth by the research, shown in Figure 7 and 8.

Figure 7. Robot picks up workpiece from the feeder table

Figure 8. Robot picks up workpiece in heating machine to the collection table

V. CONCLUSION

The research is conducted to design and build the workpiece loading robot for the high frequency induction heating machine in the production facilities in Vietnam. The robot is used to load 12-kilogram cylindrical steel workpieces, the working length of their arms are 500 mm with the accuracy of ± 1 mm. The design is based on kinematic analysis and the robot is examined by programmable control in the heavy industry. The robot worked stably, met the requirements and goals set forth by the research and is applied in production practice. Besides, other related results will be presented in subsequent studies.

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