Volume 4, Issue 8, pp. 9-13, 2020.
International Journal of Scientific Engineering and Science
ISSN (Online): 2456-7361

# Research on Designing and Manufacturing 3DOF Robot Arm

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***Abstract***— *This paper researches and designs the 3DOF robot arm to get products in the flexible manufacturing system (FMS). The Robot are responsible for picking up products after processing and putting them to the automatic product storage. From the requirement of designing and workspace, the robot arm is built with 3DOF RTT and it can control the pneumatic clamping end operation. On the theory of solving the kinematic problem (forward and reverse kinematic), the kinematic problem (kinetic energy, potential, inertia moment and differential equation of motion). The robot controller uses a PLC processor to control the working trajectory through controlling 3 motors and the servo pneumatic valve flexibly to take out the object at the last step.*

***Keywords***— *The 3DOF robot arm, Kinetic problem, kinetic energy, motion trajectory.*

## I. INTRODUCTION

In recent years, along with the development of electronic technologies, microchips, controller, image processing/ computer vision, the robotic industry has developed very strongly and become more popular. The robot arm can move like human arm. The development of robot has applied widely in my industries such as education, hospital, restaurant service, advertisement… More specially, the industrial robot arms are mechanical devices; it can be programmed with the same functions as the human arms. With high flexibility, this device is applied in many field, from welding, painting, labeling, product testing and experimenting….

Not only having flexibility and good application in many fields, industrial robot arms also save a lot of space significantly. Now, there is no need to use more human resources or heavy machine like before. Just a robotic arm can complete those tasks very quickly. Moreover, these devices not only save workspace but also help us widen it. Thanks to great support from robotics arm, we can solve more problems and save a lot of money such as labor cost or maintenance cost. Therefore, researching and mastering the robotic arm-technology is so important in Vietnam to aproach the fourth industrial revolution.

FMS - Flexible Manufacturing Systems is a system consisting of many processing devices such as numerical control machines, mounting devices, and automatic tools. These devices are designed on a modular basis and controlled by a computer or a computing system. In the FMS, the robotic arm plays an important part to transport workpieces or inspect product details. Moreover, the robotics arms can transport products from AGV self-driving vehicles into storage. Figure 2 is a 3DOF robotics arm and an automatic storage with the following principle: When the autonomous vehicles reach the waiting position, the robotic arm will rotate to the left, move to the AGV position, pick up the product and lift the arm up. After that, it will retract the arm, turn to the right and release product into position

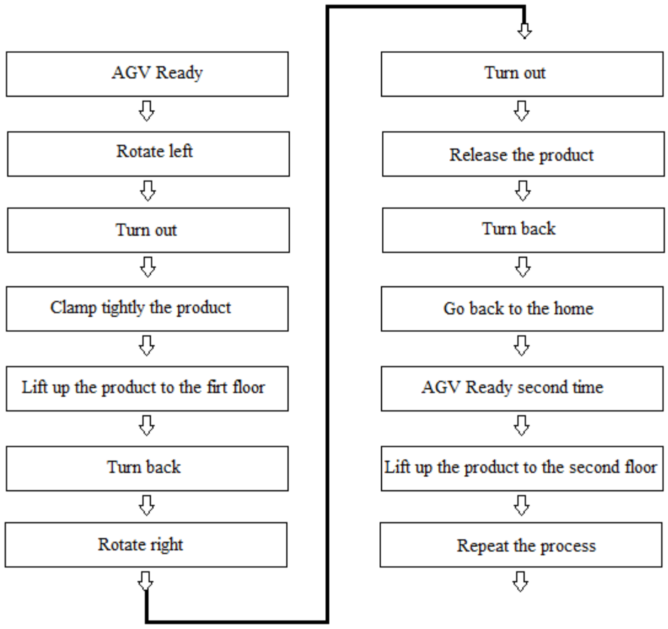


Figure 1: Diagram of the robotic work principle

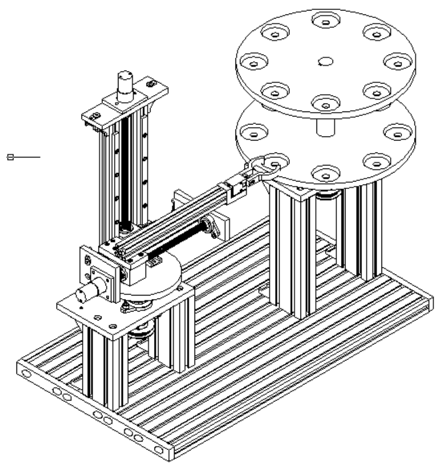

Figure 2: 3DOF robotic arm

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International Journal of Scientific Engineering and Science
Volume 4, Issue 8, pp. 9-13, 2020. ISSN (Online): 2456-7361

When the AGV car brings the second product, the robotic arm will turn to the left, move to the AGV car, pick up products, and raise the arm to the height of the second floor. After that, it will retract the arm, move to the right, and release products. When the storage has 2 products at 2 floors, the storage will automatically rotate to a new waiting position and repeat the cycle from product 1.

## II. KINEMATIC ROBOT

### A. Problem

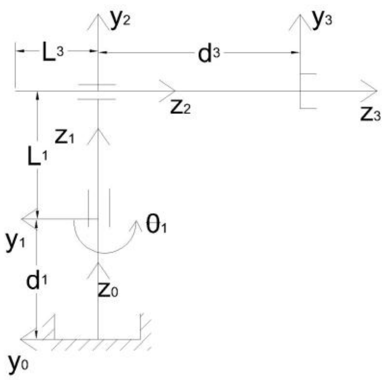


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Figure 3: Modeling of robotic coordinate systems

Table DH :

| Stage | a | $\alpha^0$ | d | $\theta^0$ |
|---|---|---|---|---|
| 1 | 0 | 0 | 0 | $\theta_1^*$ |
| 2 | 0 | $90^0$ | $L_1+d_1$ | 0 |
| 3 | 0 | 0 | $L_3+d_3$ | 0 |

Local Denavit matrix:

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

We have the matrix from 1 to 0 (stage 1)

$$^0T_1 = \begin{bmatrix} \cos\theta i & -\sin\theta i & 0 & 0 \\ \sin\theta i & \cos\theta i & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

We have the matrix from 2 to 1 (stage 2)

$$^1T_2 = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 0 & -1 & 0 \\ 0 & 1 & 0 & L_1+d_1 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

We have the matrix from 3 to 2 (stage 3)

$$^2T_3 = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & L_3+d_3 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

We have the kinetic equation of the mechanical arm:

$$^0T_3 = {}^0T_1\,.\,{}^1T_2\,.\,{}^2T_3$$

Thay $\theta_1 = 90^0$, $L_1 = 150mm$, $L_2 = 100mm$, $d_1 = 100mm$, $d_2 = 100\ mm$ into the equation, we have:

$$^0T_1 = \begin{bmatrix} 1 & -1 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$^1T_2 = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 0 & -1 & 0 \\ 0 & 1 & 0 & 250 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$^2T_3 = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 200 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$\rightarrow {}^0T_3 = \begin{bmatrix} 1 & -1 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} . \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 0 & -1 & 0 \\ 0 & 1 & 0 & 250 \\ 0 & 0 & 0 & 1 \end{bmatrix} . \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 200 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$= \begin{bmatrix} 0 & 0 & 1 & 0 \\ -1 & 0 & 0 & 0 \\ 0 & -1 & 0 & 0 \\ 0 & 0 & 250 & 1 \end{bmatrix} . \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 200 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$= \begin{bmatrix} 0 & -1 & 0 & 0 \\ 0 & 0 & -1 & 0 \\ 1 & 0 & 50000 & 250 \\ 0 & 0 & 200 & 1 \end{bmatrix}$$

Therefore, the position of robot is: $\begin{cases} x_e = 0 \\ y_e = 0 \\ z_e = 250 \end{cases}$

The robot's direction is:

$$RE = \begin{bmatrix} 0 & -1 & 0 \\ 0 & 0 & -1 \\ 1 & 0 & 50000 \end{bmatrix}$$

### B. Reverse Problem

Stage O0

$$0T1 = \begin{bmatrix} \cos\theta_1 & -\sin\theta_1 & 0 & 0 \\ \sin\theta_1 & \cos\theta_1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

⇨ $0P1 = [0 \quad 0 \quad 0]T;$

⇨ $0R1 = \begin{bmatrix} \cos\theta_1 & -\sin\theta_1 & 0 \\ \sin\theta_1 & \cos\theta_1 & 0 \\ 0 & 0 & 1 \end{bmatrix}$

We have a long velocity of the joint O0:

$$V1 = \frac{Rod}{dt}(0P1) = [0 \quad 0 \quad 0]T$$

Acceleration of joint 00:

$$O0 = a1 = \frac{Rod}{dt}(0V1) = [0 \quad 0 \quad 0]T$$

Wave element of joint O0

$$0W1 = 0R_1^T\,.\,0R_1^0 =$$

$$\begin{bmatrix} \cos\theta_1 & -\sin\theta_1 & 0 \\ \sin\theta_1 & \cos\theta_1 & 0 \\ 0 & 0 & 1 \end{bmatrix} . \begin{bmatrix} -\sin\theta_1 & 0 & \cos\theta_1 \\ \cos\theta_1 & 0 & -\sin\theta_1 \\ 0 & 0 & 0 \end{bmatrix}$$

$$= \begin{bmatrix} -\cos\theta_1.\sin\theta_1 & \sin^2\theta_1 & \cos\theta_1 \\ \cos^2\theta_1 & -\sin\theta_1.\cos\theta_1 & \sin\theta_1 \\ 0 & 0 & 0 \end{bmatrix}$$

International Journal of Scientific Engineering and Science
Volume 4, Issue 8, pp. 9-13, 2020. ISSN (Online): 2456-7361

Angular velocity of the joint O0:

$$0U1 = [0 \quad \cos\theta_1 \quad \cos^2\theta_1]$$

Angular acceleration of the joint O0:

$$0\vec{a}1 = \frac{Rod}{dt}(0\vec{U}1) = [0 \quad -\sin\theta_1 \quad -2\sin^2\theta_1]$$

- At stage O1

$$1T2 = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 0 & -1 & 0 \\ 0 & 1 & 0 & l_1 + d_1 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

⇨ $1P2 = [0 \quad 0 \quad l_1 + d_1]T;$

⇨ $1R2 = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 0 & -1 \\ 0 & 1 & 0 \end{bmatrix}$

We have velocity of joint O1:

$$V2 = \frac{Rod}{dt}(1P2) = [0 \quad 0 \quad 0]T$$

Acceleration of joint O1:

$$O1 = a2 = \frac{Rod}{dt}(1V2) = [0 \quad 0 \quad 0]T$$

Wave element of joint O1

$$1W2 = 1R_2^T \,.\, 1R_2^0 = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 0 & -1 \\ 0 & 1 & 0 \end{bmatrix} . \begin{bmatrix} -\sin\theta_2 & -\cos\theta_2 & 0 \\ \cos\theta_2 & -\sin\theta_2 & 0 \\ 0 & 0 & 0 \end{bmatrix}$$

$$= \begin{bmatrix} -\sin\theta_2 & 0 & \cos\theta_2 \\ \cos\theta_2 & 0 & \sin\theta_2 \\ 0 & 0 & 0 \end{bmatrix}$$

Angular velocity of joint O1:

$$1U2 = [0 \quad 0 \quad \cos\theta_2]$$

Angular acceleration of joint O1:

$$1\vec{a}2 = \frac{Rod}{dt}(1\vec{U}2) = [0 \quad 0 \quad -\sin\theta_2]$$

- At stage O2

$$2T3 = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & l_3 + d_3 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

⇨ $2P3 = [0 \quad 0 \quad 0]T;$

⇨ $2R3 = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix}$

We have velocity of joint O2:

$$V3 = \frac{Rod}{dt}(2P3) = [0 \quad 0 \quad 0]T$$

Acceleration of joint O2:

$$O2 = a3 = \frac{Rod}{dt}(2V3) = [0 \quad 0 \quad 0]T$$

Wave element of joint O2

$$2W3 = 2R_3^T \,.\, 2R_3^0 = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} . \begin{bmatrix} -\sin\theta_3 & -\cos\theta_3 & 0 \\ \cos\theta_3 & -\sin\theta_3 & 0 \\ 0 & 0 & 0 \end{bmatrix}$$

$$= \begin{bmatrix} -\sin\theta_3 & 0 & \cos\theta_3 \\ \cos\theta_3 & 0 & \sin\theta_3 \\ 0 & 0 & 0 \end{bmatrix}$$

Angular velocity of joint O2:

$$2U3 = [0 \quad 0 \quad \cos\theta_3]$$

Angular velocity of joint O2:

$$2\vec{a}3 = \frac{Rod}{dt}(2\vec{U}3) = [0 \quad 0 \quad -\sin\theta_3]$$

## 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.

$\tau$ : Drive force.

Q :Coordinates system.

- :Robot kinematic parameters

Robot parameter table:

| Joint | Center position (m) | | | Mass (kg) |
|---|---|---|---|---|
| | xC | yC | zC | |
| 1 | -0.0694 | -0.1352 | -0.0007 | 2.325 |
| 2 | -0.2758 | -0.0045 | 0 | 1.564 |
| 3 | -0.0094 | -0.0008 | 0.0685 | 1.021 |

Table 1: Center position of stage

| Joint | Moment of inertial mass of the stage( kg.m2) | | | | | |
|---|---|---|---|---|---|---|
| | Ixx | Iyy | Izz | Ixy | Iyz | Izx |
| 1 | 2.5485 | 1.6323 | 2.1458 | 0.6297 | -0.0085 | -0.0051 |
| 2 | 0.0332 | 0.3621 | 0.3517 | 0.001 | 0.00010 | -0.0001 |
| 3 | 0.1553 | 0.1634 | 0.0255 | 0.000 | 0.0008 | 0.00789 |

Table 2: Moment of inertial mass of the stage to the center position Ci

❖ Steps to finish:

➢ Step 1: Calculate the transmission matrix ${}^0A_{Ci}$:

with :

$${}^0A_{Ci} = {}^0A_i \, {}^iA_{Ci}$$

From these transmission matrix ${}^0A_{Ci}$ we can infer rotating matrices ${}^0R_{Ci}$ and position vector ${}^0r_{Ci}$.

➢ Step 2: Calculate Jacobi matrix $J_{Ti}$ and $J_{Ri}$.

Position vector ${}^0r_{Ci} \rightarrow$ Jacobi matrix translational $J_{Ti}$.

Have : ${}^0r_{Ci} = J_{Ti}q$, with $q = [q_1, q_2, q_3, q_4, q_5, q_6]^T$

Jacobi matrix rotation ${}^0R_{Ci} \rightarrow$ Jacobi matrix rotation $J_{Ri}$.

Matrix:

$$\tilde{\omega}^i = {}^0R_{Ci}^T \, {}^0\dot{R}_{Ci} = \begin{bmatrix} 0 & -\omega_z & \omega_y \\ \omega_z & 0 & -\omega_x \\ -\omega_y & \omega_x & 0 \end{bmatrix}$$

$$\omega^{i} = \begin{bmatrix} \omega_x & \omega_y & \omega_z \end{bmatrix}^T = J_{Ri} q$$ , with

$$q = [q_1, q_2, q_3, q_4, q_5, q_6]^T$$ .

- Step 3: Calculate the matrix of mass .

$$M(q) = \left[ \sum_{i=1}^{n} (J_{Ti}^T m_i J_{Ti} + J_{Ri}^T \Theta_{Ci}^{Ci} J_{Ri}) \right]_{6\times6}$$

- Step 4: Calculate the matrix of coriolis and centrifugal inertial forces.

$$C(q,\dot{q})\dot{q} = \left[ c_j(q,\dot{q})\dot{q} \right]_{6\times1}$$

với
$$c_j(q,\dot{q})\dot{q} = \sum_{k,l=1}^{n} (k,l;j)\dot{q}_k \dot{q}_l$$

Trong đó:
$$(k,l;j) = \frac{1}{2}\left(\frac{\partial m_{kj}}{\partial q_l} + \frac{\partial m_{lj}}{\partial q_k} - \frac{\partial m_{kl}}{\partial q_j}\right)$$

- Step 5: Calculate the matrix of the forces that are not:

$$\Pi = \Pi(q) = g \sum_{i=1}^{n} m_i z_{Ci}$$

Trong đó: $G(q) = \left[ g_j(q) \right]_{n\times1}$ với $g_j(q) = \dfrac{\partial \Pi}{\partial q_j}$

- Step 6: Force / torque control.

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

## IV. 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 3DOF robot arm trajectory according to the method of controlling the space motion trajectory.

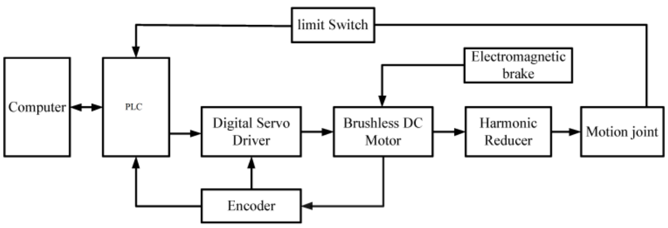


Figure 4: Control diagram in matching space.

Siemens S7-1200 PLC control system controls 3 motors simultaneously controlling 3 stage 1, 2, 3 and stage motion movements using pneumatic valve control on the pneumatic release clamp cylinder.

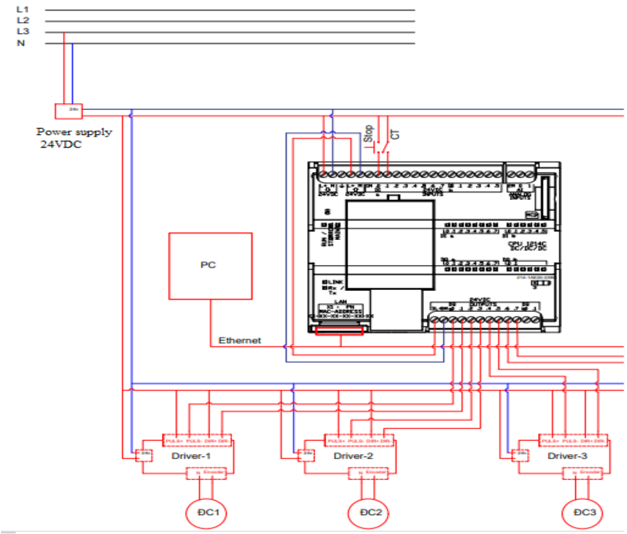


Figure 5: Controlling principle diagram

## V. Conclusion

From the study of the theoretical calculations of dynamic problems and differential equations of motion to calculate the motion and working trajectories of the 3DOF machine arm. Based on the controlling theory to build a 3DOF robot controlling system with 3 motors controlled according to the matching space, the paper researches and designs 3DOF robots to pick up products from AGV self-driving vehicles into the automatic product stage. In the next research direction, the system will upgrade to self-select with the camera placed at the last operation stage to self-adjust the product position deviations.

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