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Researching and Building Automatic Painting Algorithms for a 5 Degree-of-Freedom Robot

PHUNG TRI CONG, NGUYEN DUY ANH
Department of Mechanical Engineering, Ho Chi Minh city University of Technology, VNU-HCM, Vietnam
Email: ptcong@hcmut.edu.vn, duyanhnguyen@hcmut.edu.vn

Abstract: Nowadays the application of industrial robots in manufacturing is so popular, especially in painting field. The painting work can affect to the health of workers. Thus, robots can replace people in this harmful activity such as in car manufacturing. This paper concentrates on building automatic painting algorithms for a given 5 degree-of-freedom (DOF) robot. First we look for the workspace of the robot. From this workspace, a complete system is designed including a 5-DOF robot, a translational part, and a painting object. Next, we solve position kinematic problems for the robot including forward kinematic and inverse kinematic problem. After that, automatic painting algorithms are built so that the robot can paint a planar surface and a cylindrical surface. These algorithms are verified by simulation using MATLAB. Finally, an experiment with real model is also considered to test proposed algorithms.

Keywords: *Painting System, 5-DOF Robot, Forward Kinematic, Inverse Kinematic, Path Tracking Algorithm*

Introduction:
Industrial robots play an important role in manufacturing because they can increase productivity and make product becoming better. Besides, robots also protect human from poisonous environments and dangerous workings. Painting is a necessary process in many manufacturing fields such as in car factory. This work will affect to the quality of the product. Because the quality of the product depends on the worker and will reduce according to a long time. Figure 1 shows an example of using painting robot.

Figure 1: Painting Robot in Industry

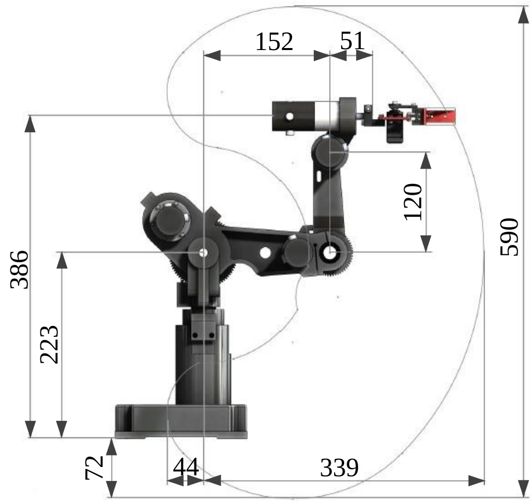
Building an automatic painting system using robot can give us several advantages. The first one is making product more reliable and have more quality. Second, painting is a bored work so that workers cannot make in a long time, but robot can do this work during 24 hours per day. Third, painting room has poisonous air and affect to the health of the worker.
Powder coating nowadays is used frequently comparing to a conventional liquid paint. Powder coating does not require a solvent to keep the blinder and filler parts in a liquid suspension form. The coating is typically applied electrostatically and is then cured under heat to allow it to flow and form a skin. Because powder coating does not have a liquid carrier, it can produce thicker coatings than conventional liquid coatings without running or sagging, and powder coating produces minimal appearance differences between horizontally coated surfaces and vertically coated surfaces. We will build the painting algorithm based on this method.
In this paper, we concentrate on researching and building an automatic painting algorithms for a given object. Two surfaces chosen are planar surface and cylindrical surface. The algorithm is verified by simulation and experiment. The paper includes six parts: description about a 5-DOF robot, designing painting system, solving forward and inverse kinematic problems, building automatic control algorithm, simulation results and experiment results.

Description about 5-DOF Robot:
The robot used in this paper is a 5-DOF robot including 3-DOF for position and 2-DOF for orientation of the painting gun. The shape of robot can be seen in figure 2. Each joint of the robot is controlled by a DC servo motor from Harmonic Driver Company. The information about these motors is shown in table 1. The workspace of the robot can be shown in figure 3.

Table 1: Information about joints of robot

Joint	Gear	Number of Pulse/Revolution	Maximum Torque (Nm)
1	110	22000	20
2	110	61600	50
3	100	50000	25
4	100	20000	5
5	50	10000	3.5

Figure 2: A 5-DOF robot used in the paper



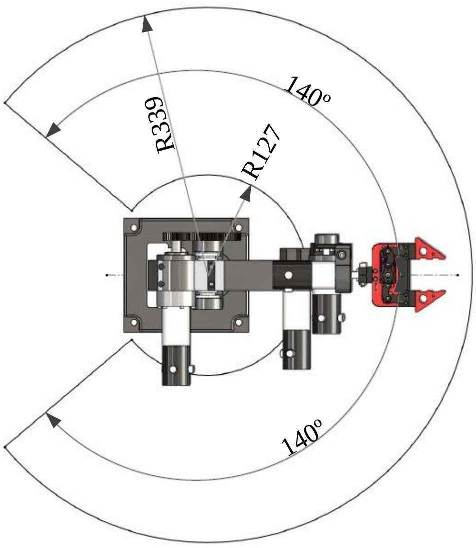


Figure 3: Workspace of the robot

Designing Painting System:
Because the robot has 5 DOF, it cannot move to all the surface of the object. So we need to make the object move along one axis. The robot now just moves in a plane and paints a part of the object. After finishing this part, the object is translated to the next position and robot continue painting other part.

Figure 4: Automatic painting system

Figure 4 shows our system design. The system include a given 5-DOF robot, a translation part, and a painting object. The translation part includes a screw and a nut to make the object translation.

Forward and inverse kinematic problems:
Next, we solve inverse kinematic and forward kinematic of the robot. The configuration of the robot can be shown in figure 5. DH parameters are shown in table 2.

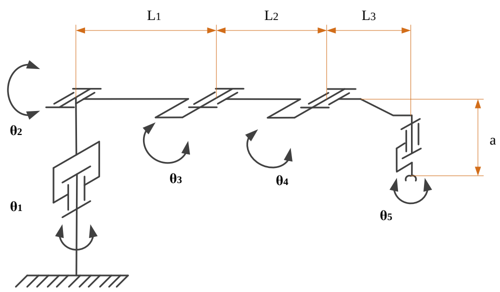


Figure 5: Configuration of robot

Table 2: DH parameters

Link i	a_i (mm)	α_i (^{0})	d_i (mm)	θ_i (^{0})
1	0	90	0	θ_1
2	L_1	0	0	θ_2
3	L_2	0	0	θ_3
4	L_3	90	0	θ_4
5	0	0	a	θ_5

Based on DH parameters, we can calculate the transformation matrix between the tool frame and the base frame.

$$ {}^0_5T = \begin{bmatrix} s_1s_5 + c_5c_1c_{234} & c_5s_1 - s_5c_1c_{234} & c_1s_{234} & X \\ c_5s_1c_{234} - c_1s_5 & -c_5c_1 - s_5s_1c_{234} & s_1s_{234} & Y \\ c_5s_{234} & s_5s_{234} & -c_{234} & Z \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (1) $$

Where

$$ X = ac_1s_{234} + L_1c_1c_2 + L_2c_1c_{23} + L_3c_1c_{234} \quad (2) $$

$$Y = as_1 s_{234} + L_1 c_2 s_1 + L_2 s_1 c_{23} + L_3 s_1 c_{234} \quad (3)$$

$$Z = -ac_{234} + L_1 s_2 + L_2 s_{23} + L_3 s_{234} \quad (4)$$

In these equation we assume that

$$c_{234} = \cos(\theta_2 + \theta_3 + \theta_4) \quad (5)$$

$$s_{234} = \sin(\theta_2 + \theta_3 + \theta_4) \quad (6)$$

$$c_{23} = \cos(\theta_2 + \theta_3), s_{23} = \sin(\theta_2 + \theta_3) \quad (7)$$

$$s_i = \sin\theta_i, c_i = \cos\theta_i \quad (8)$$

Next, we will solve the inverse kinematic problem. During painting process, we don't need to control the fifth joint of the robot because the painting gun is symmetric. So we just need to solve the inverse problem for four joints of the robot. Assuming that we receive the positon and orientation of the robot as in equation

$$ {}^0_5T = \begin{bmatrix} {}^0_5T_{11} & {}^0_5T_{12} & {}^0_5T_{13} & x \\ {}^0_5T_{21} & {}^0_5T_{22} & {}^0_5T_{23} & y \\ {}^0_5T_{31} & {}^0_5T_{32} & {}^0_5T_{33} & z \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (9)$$

From that we can calculate θ_1

$$\theta_1 = \arctan 2(y, x) \quad (10)$$

$$\theta_2 + \theta_3 + \theta_4 = \arctan 2\left(-\left(c_1\, {}^0_5T_{13} + s_1\, {}^0_5T_{23}\right), {}^0_5T_{33}\right) \quad (11)$$

Next we calculate θ_3

$$c_3 = \frac{D + E - L_1^2 - L_2^2}{2L_1 L_2} \quad (12)$$

$$D = \left(c_{234}\left(c_1 x + s_1 y\right) + s_{234} z - L_3\right)^2 \quad (13)$$

$$E = \left(s_{234}\left(c_1 x + s_1 y\right) - c_{234} z - a\right)^2 \quad (14)$$

$$s_3 = \pm\sqrt{1 - c_3^2} \quad (15)$$

$$\theta_3 = arc\tan 2\left(s_3, c_3\right) \quad (16)$$

After that, we calculate θ_2

$$c_2 = \frac{F + L_2 s_3\left(z + ac_{234} - L_3 s_{234}\right)}{\left(L_1 + L_2 c_3\right)^2 + \left(L_3 s_3\right)^2} \quad (17)$$

$$F = \left(c_1 x + s_1 y - as_{234} - L_3 c_{234}\right)\left(L_1 + L_2 c_3\right) \quad (18)$$

$$s_2 = \frac{G - L_2 s_3\left(c_1 x + s_1 y - as_{234} - L_3 c_{234}\right)}{\left(L_1 + L_2 c_3\right)^2 + \left(L_3 s_3\right)^2} \quad (19)$$

$$G = \left(z + ac_{234} - L_3 s_{234}\right)\left(L_1 + L_2 c_3\right) \quad (20)$$

$$\theta_2 = arc\tan 2\left(s_2, c_2\right) \quad (21)$$

Finally we can calculate θ_4 from equations (11), (16), and (21).

Control Algorithm:

In this part, we describe our algorithm for automatic painting system. First, we attach the object on the translational part. Next we control the robot to the working position. After that, we translate the object a distance of 5mm. We control the robot to paint the surface of the object two times. After finish, we control robot to working position and wait. Next, we continue translate the object and robot will continue painting until it paints all the surface of the object. Figure 6 shows our control algorithm.

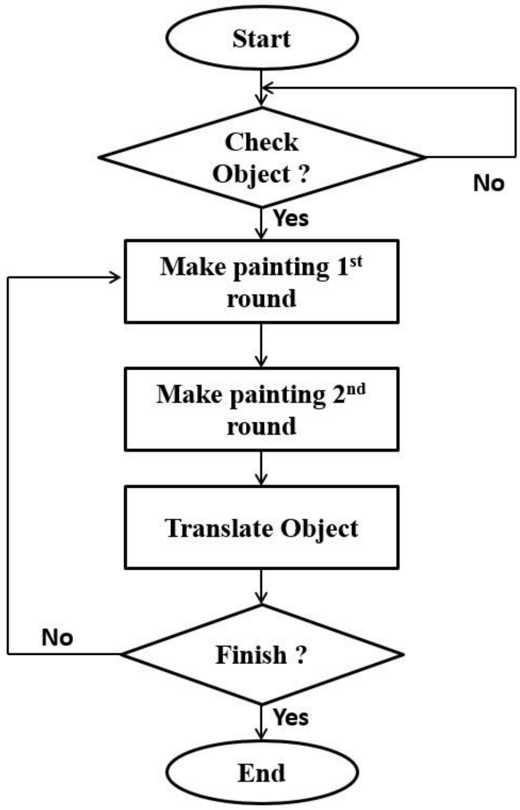


Figure 6: Control algorithm of painting process

Simulation Results:

In this part, we show simulation results. First we design the robot in SolidWorks. After that, we import this file into MATLAB using Sim Mechanics Tool. The model of the robot can be seen in figure 7.

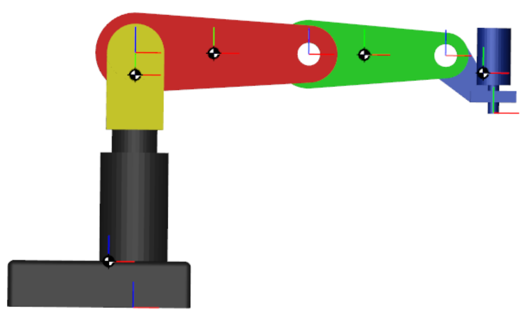


Figure 7: Robot model in MATLAB

Next we will simulate the robot to track the planar surface and the cylindrical surface. In one plane, they become a line and a circle. So we will simulate the robot to track a line and a circle as in figure 8. In this figure, blue curve is desired curve and small red circle is simulated curve. The result shows that the robot can track the desired curve.

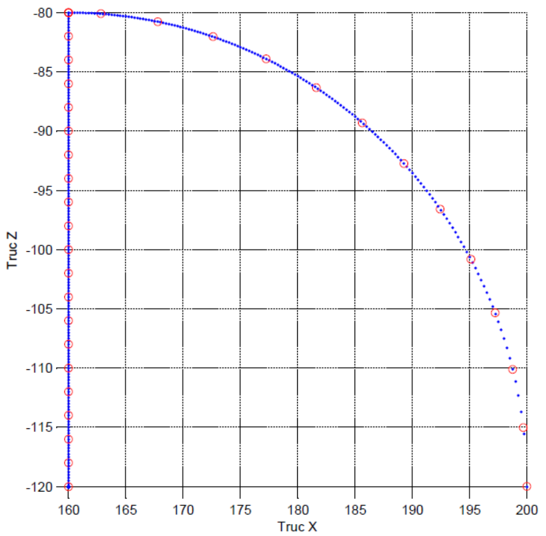


Figure 8: Desired and simulated trajectory

During the simulation process, the painting gun is normal to the surface of the painting object. Figure 9 show the result when robot paints a planar surface and figure 10 show the result when robot paints a circular surface.

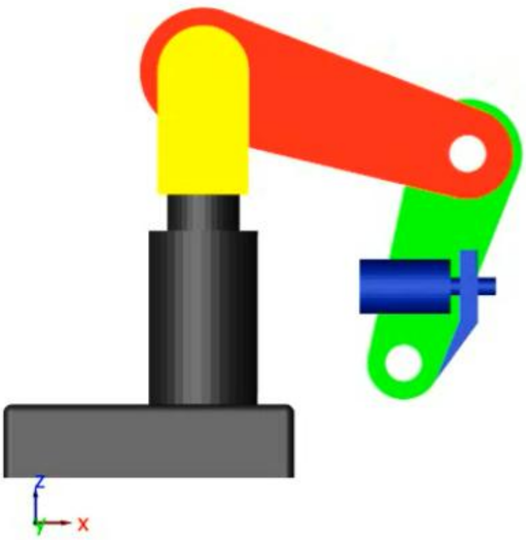


Figure 9: Simulation result of painting planar surface

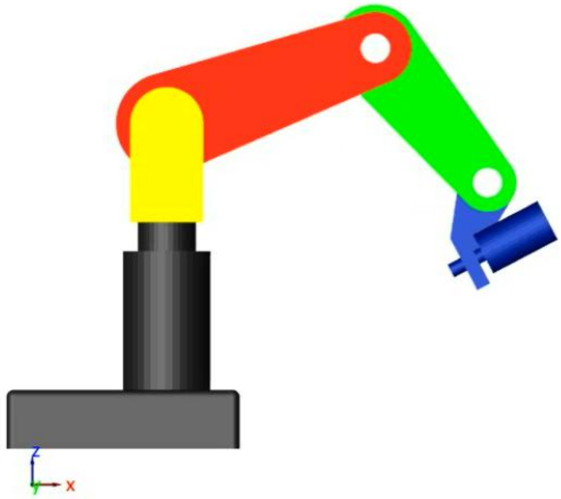


Figure 10: Simulation result of painting cylindrical surface

Experimental Results:

In this part, we will test with real model. Figure 11 shows the controller of the robot. Each joint of the robot is controlled by a commercial driver and a microcontroller PIC18F4680. These microcontrollers communicate together by CAN protocol. At this time, we verify our tracking algorithm that the robot can track a line trajectory and a circular trajectory. The experimental setup can be seen in figure 12.

In the experiment, we control the robot so that it can track a square of 50mm and a circle which diameter of 40mm. Figure 13 shows the result when robot track a square of 50 mm and give us the error of 3%. Figure 14 shows the result when robot track a circular curve whose diameter is 40mm and give the error of 3.75%.

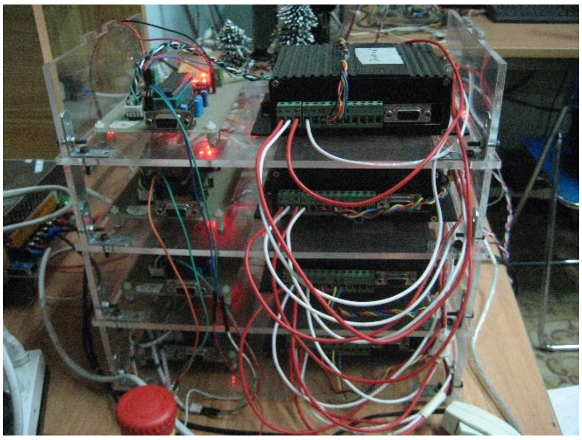


Figure 11: Controller of 5-DOF robot

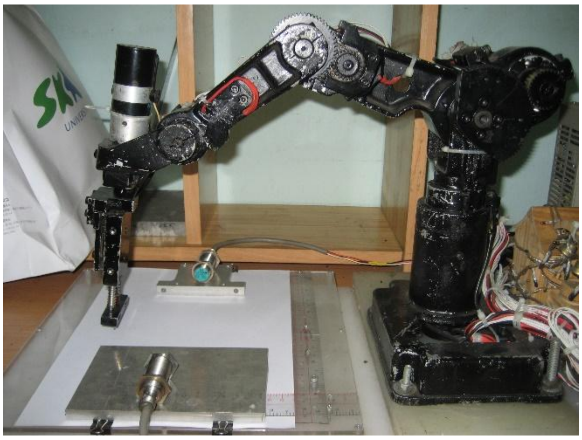


Figure 12: Experimental setup

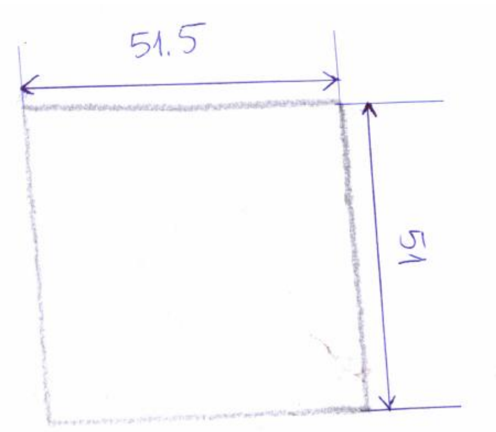


Figure 13: Experimental result when robot track a square curve

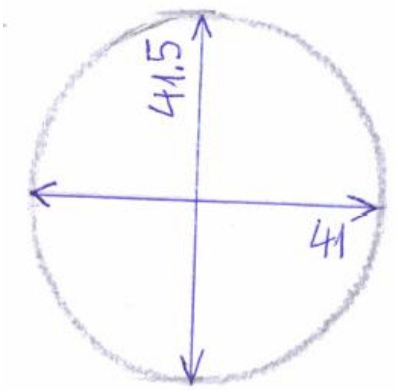


Figure 14: Experimental result when robot track a circular curve

Conclusion:

In this paper, we have built an automatic painting algorithm for a planar surface and a cylindrical surface. Our system design includes a 5-DOF robot, a translational component, and a painting object. The algorithm has been verified by simulation in MATLAB. In the experimental result, we just check the linear trajectory and circular trajectory and the results can be acceptable. In the future, we will build complete system and check our proposed algorithm.

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