Design of a Painting Robotic Cell for Industrial Applications

[1*]Atef A. ATA [2]Alaa ELEYAN
[1] Department of Mechatronics Engineering, Mevlana University, Turkey
[2] Department of Electrical and Electronics Engineering, Mevlana University, Turkey
{atef,aeleyan@mevlana.edu.tr}

Abstract:

The painting applications for industrial robots have been increased extensively in the last decades. Robots are known for their accuracy and repeatability and this will help in getting smooth and homogeneous operations which humans cannot perform repeatedly. Normally, the painting robots have six degrees-of-freedom (DOF) to allow the painting of complex shapes and surfaces. The main objectives of this paper is to design a 3-DOF robot that could be used for painting applications. The proposed robot is composed of three DOF and can be applied for painting plane dividers accurately and in a homogeneous pattern. This reduces the cost and simplifies the kinematic and dynamic analysis and ensures the homogeneity of the painting at the same time. This robot can be used to paint multiple color effectively without interfering from any human. The end-effector consists of two main parts, a color sensor and a spray gun. The color sensor can detect the required color of the divider based on a small sticker pasted on the divider. As soon as the color is detected, the controller moves a specific rack to be aligned with the reservoir filled of this color. A pump will start operating and divider will be painted in vertical strips starting from bottom-up. When divider painting finishes, the rack returns to its original position waiting for the next divider.

Key words: Painting robot, spray gun, color sensor, homogeneous, control strategy

1. Introduction

Normally the spray painting is carried out by a human (Manual), or by spray guns fixed to stationary base (Hard Automation) or through a six-axes robot programmed through a complex trajectory (Fully Automated). Robots handle a range of dissimilar parts painted at a high production rates. For example, some automotive manufacturer require finishers to paint all plastic trim parts synchronously for better color matching, this is an ideal application for a robot. Once the robot is programmed, it paints millions of parts with little variations [1]. The speed of the robot plays an important part in the homogeneity of the painting thickness and its finishing. Typically pattern distortion occurs around 5 ft/s, so a robot that can move faster has a limited benefits for spraying. So it is recommended to make a spray test to adjust a trade-off between the robot speed and the painting quality.

Human operators tend to be less consistent and efficient with paint which results in a significant paint waste. It is also interesting how manual touch-up in one area inevitably results in overspray in another. Using robot that moves with constant speed will save a lot of paints and keeps the homogeneity of the surface as well. Robots spraying solvent should be carefully selected against explosion. In many cases especially for liquid paint applications air purge systems are recommended [1].

*Corresponding author: Address: Faculty of Engineering, Department of Mechatronics Engineering Mevlana University, 42003, Konya TURKEY. E-mail address: atef@mevlana.edu.tr, Phone: +903324243(1423) Fax: +902312414344

The first painting robot to have integrated paint process equipment was introduced in 1996. The FANUC P-200 was the first robot design around the painting equipment. For example, to minimize the paint waste, color changes were mounted in the arm of the robot as close as possible to the spray applicator. Also, the paint fluid supply lines were mounted through the centre of the robot base, enabling the robot to rotate around the paint line as opposed to having them managed to external means. A spray painting model was established in the work of Suh et al. [2] and Arikan [3], where mathematical relationships between the painting thickness and other painting process parameters were analyzed. Anand et al. [4] developed an on-line robotic spray painting system using machine vision.
One of the drawbacks with painting robot is the color change losses. To overcome this problem, the color changer must be incorporated into the atomizer such as the EcoBell2 ICC. The paint lines are connected directly to the atomizer and each color has a separate dosing pump which solves the cleaning problem of each line. The individual dosing pumps are connected to the servo motor via switchable pneumatic coupling. As a result, only one pump motor is needed for the entire multi-pump systems [4].
This paper proposes a simple, accurate and cost-effective painting robots that can be used for vertical divider painting. The robot has a cylindrical structure with only three DOF and the end-effector consists of two main parts, the spray gun as well as the color sensor. The divider is approaching the robot using a conveyor belt that moves at constant speed that stops in front of the robot to detect the color that must be painted through a sticker posted on the divider. This color sensor sends a triggering signal to the controller to start painting the divider and at the same time the conveyor belt is going to move slowly while the painting is carried out.

2. Basics of Robot Design

Consider the three DOF cylindrical robotic arm as shown in Figure 1. The robot is assumed to move in the vertical plane and has three links. The structure of the robot enables the spray painting gun to paint a moving divider easily and effectively. The end-effector of the robot is equipped with a color sensor as well as a spray painting gun. The color sensor is secured inside a housing which is always close and can be opened only when a divider is placed in front of the robot to detect the color of the sticker posted on the divider to protect the sensor from the painting waste. The cylindrical structure of the proposed painting robot is stiff enough to prevent the end-effector from vibration and bending problems and to reach every point of the vertical divider accurately and easily. The end-effector with its contents can approach, depart, and move up and down to cover the whole workspace.

3. Procedure Analysis

The conveyor belt is controlled to move at constant speed which will be relatively low to allow the spray painting gun to give a homogeneous thickness for the painting. The procedure for the painting process will be as follows:

1-The divider will approach the robotic station through the conveyor belt running at constant speed and it will stop in front of the robot based on a signal from a proximity sensor attached on the conveyor belt.

2-The end-effector is going to move near the sticker indicating the color of the divider and a color sensor is released from its casing to detect the color of the sticker.

3-The color of the sticker acts like a triggering signal and the controller moves the rack and pinion drive to be centered with the indicated color reservoir.

4-The sensor will return back to its case and the pump starts painting the vertical divider in vertical strips from bottom up while it is moving at low constant speed.

5-Upon finishing painting the divider, another divider will be approaching. The color sensor will detect the sticker color. If the color is same as the color of previous divider, the pump starts painting as normal.

6-If the color is different from the previous one, the rack and pinion drive will be centered on the solvent position and the pump starts pushing the solvent to clean the tube preparing for the new color.

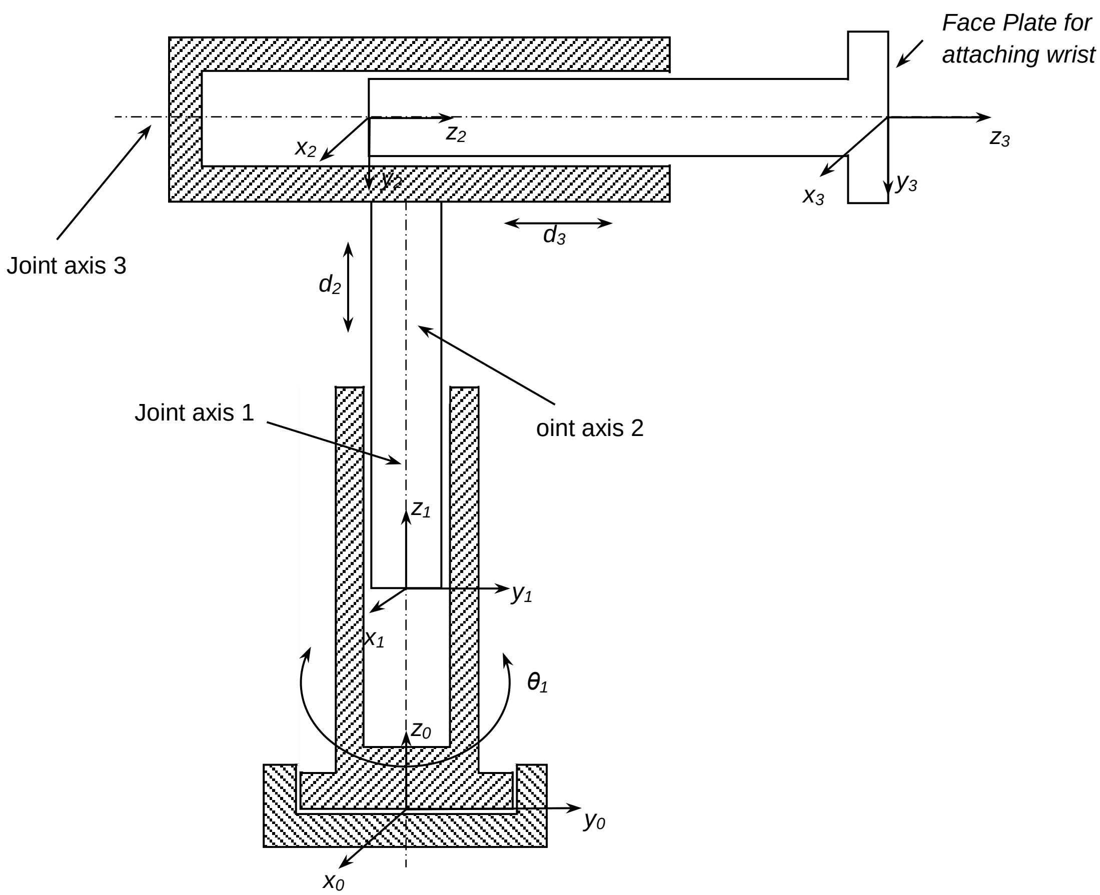

Figure 1. Configuration of a 3-DOF Cylindrical robot arm [5]

The schematic diagram for the proposed cell that will be attached to the robot arm including its details is shown in Figure 2. The cylindrical robot consists of rotation of θ_1 around the Z_0 axis followed by translation of d_2 along the Z_1 axis and finally translation of d_3 along the Z_2 axis. The parameters are given in Table 1. The transformation matrices are given according to Denavit-Hartenberg transformation.

Table 1. Parameters Table

Link Number	θ	d	a	α
1	θ_1	0	0	0
2	0	d_2	0	-90
3	0	d_3	0	0

$$ {}^{0}T_{1} = \begin{bmatrix} C\theta_1 & -S\theta_1 & 0 & 0 \\ S\theta_1 & C\theta_1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad {}^{1}T_{2} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & -1 & 0 & d_2 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad {}^{1}T_{2} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & d_3 \\ 0 & 0 & 0 & 1 \end{bmatrix} $$

The transformation from the end-effector to the robot base coordinate is given by:

$$ {}^{0}T_{3} = \begin{bmatrix} C\theta_1 & 0 & -S\theta_1 & -d_3 S\theta_1 \\ S\theta_1 & 0 & C\theta_1 & d_3 C\theta_1 \\ 0 & -1 & 0 & d_2 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{1} $$

Where S represent sin and C represents cosine.
Based on Equation (1), the Jacobian of the robot is the relation between the velocity of the end-effector and the velocity of each joint and is given by:

$$ \begin{bmatrix} \dot{x} \\ \dot{y} \\ \dot{z} \end{bmatrix} = \begin{bmatrix} -d_3 C\theta_1 & 0 & S\theta_1 \\ -d_3 S\theta_1 & 0 & C\theta_1 \\ 0 & 1 & 0 \end{bmatrix} \begin{bmatrix} \dot{\theta} \\ \dot{d}_2 \\ \dot{d}_3 \end{bmatrix} \tag{2} $$

Since the cylindrical robot has the simplest kinematic structure, it is possible to control the velocity of the end-effector to achieve the purpose of homogeneous painting. Based on the proposed design, we have two phases the detection of the color phase and the painting phase. For the first phase the angular velocity of the first joint $\dot{\theta}_1$ as well as the horizontal velocity of the third joint $\dot{d}_3$ are adjusted where the vertical motion of the second joint $\dot{d}_2$ is set to be zero since the home position of the robot is set at the maximum value for d_2 . The second phase starts after the completion of the first phase and since the spray paint fixed at the end-effector is going to move vertically up and down at a constant speed, it can be assumed that the angular position θ_1, the angular velocity of the first joint $\dot{\theta}_1$ as well as the horizontal velocity of the third joint $\dot{d}_3$ vanish. This allows the designed to control the vertical velocity of the end-effector based on the robot Jacobian from Equation (2).
The design of the proposed end–effector that will be fixed on the end point of the last link is shown in Figure 3.

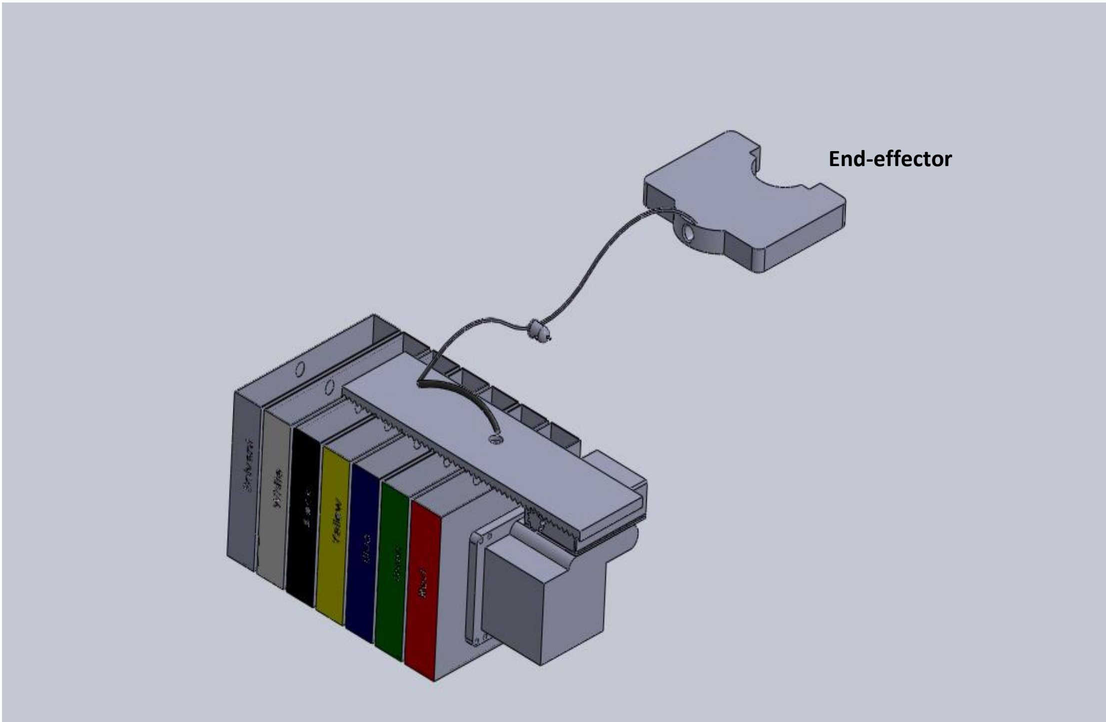

Figure 2. Conceptual design of the proposed mechanism

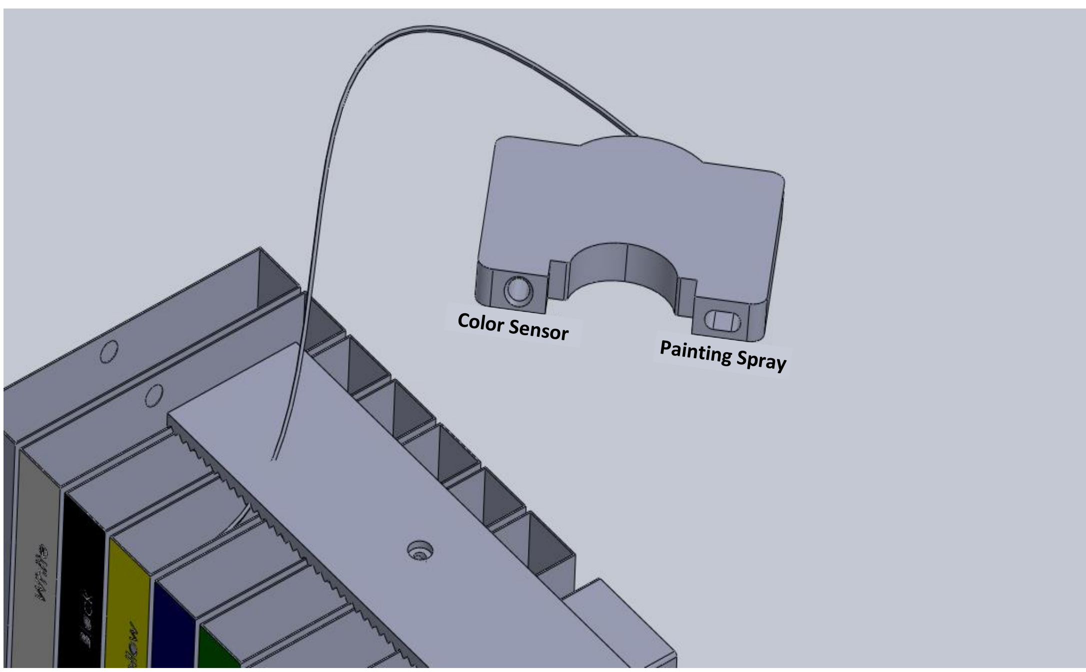

Figure 3. Details of the end-effector

4. Proposed Experimental Setup

The proposed system consists of the following components:

1- The Conveyor Belt:

A conveyor belt taking the U shape is designed around the robot arm. The conveyor belt is controlled by Programmable Logic Controller (PLC) that communicates with the robot controller for the execution of the painting process. It is equipped with proximity sensors to stop the dividers as they approach the robot position. As soon as the divider stops, the PLC sends a signal for the robot controller to start working. After the divider is painted the robot controller sends another signal to the PLC to start moving the conveyor belt and another divider is coming for painting.

2- The Color Sensor:

The main objective of the color sensor is to detect the color of a small sticker posted on the divider and sends a signal to the attached unit controller about the color to be painted. There are many color sensors that can be used such as the one by Industrial automation [6, 7] that was used by the author in a previous project. The only drawback is the detecting distance is about 15 millimeters. Another example is the ColorMax-1000™ color sensor produced by EMX Industries Inc. which sees up to 15 colors and RGB intensity [8]. This color sensor comes also with ColorMax-I/O that allows the user to interface the sensor with the computer or PLC controller.

3-The Paint Reservoir:

A reservoir with different painting colors and a separate section for solvent is attached to the robot as a separate unit. As soon as the color sensor detects the color to be painted a signal will be sent to the unit controller to move the rack and pinion drive to the selected color position. The pump starts pumping the paint until the divider is painted and then stops based on time calculation.

4- The Unit Controller:

The main objective of the controller is coordinating the attached unit to the robot including the reservoir, the color sensor, the rack and pinion drive, the pump and the spray gun. It will receive the signal from the color sensor about the specific color to be painted and sends a signal for the rack and pinion to start moving to the selected reservoir. It will also create and coordinate the motion of the rack and pinion to approach the reservoir solvent if the consecutive colors are not the same.

5- The End-Effector

The end-effector of the robot arm has a special design since it will carry out the spray gun and a place for the color sensor as well in a protected shield to allow it to work properly and not to be affected by the painting spray. The color sensor will be covered by a black circle similar to the one used in Cameras and it will be removed automatically when the end-effector is approaching the vertical divider to detect its color. As soon as the color is detected and before the pump starts pumping the paint, the cover will return back to its original place to cover the color sensor.

Upon building the proposed system a parametric study based on the actual performance analysis of the system will be carried out to select the optimal parameters of the proposed system. One of the main parameters that will be examined is the optimum speed of the conveyor belt as well as the vertical speed of the end-effector for accurate and homogeneous painting thickness.

The flowchart for the proposed algorithm is shown in Figure 4.

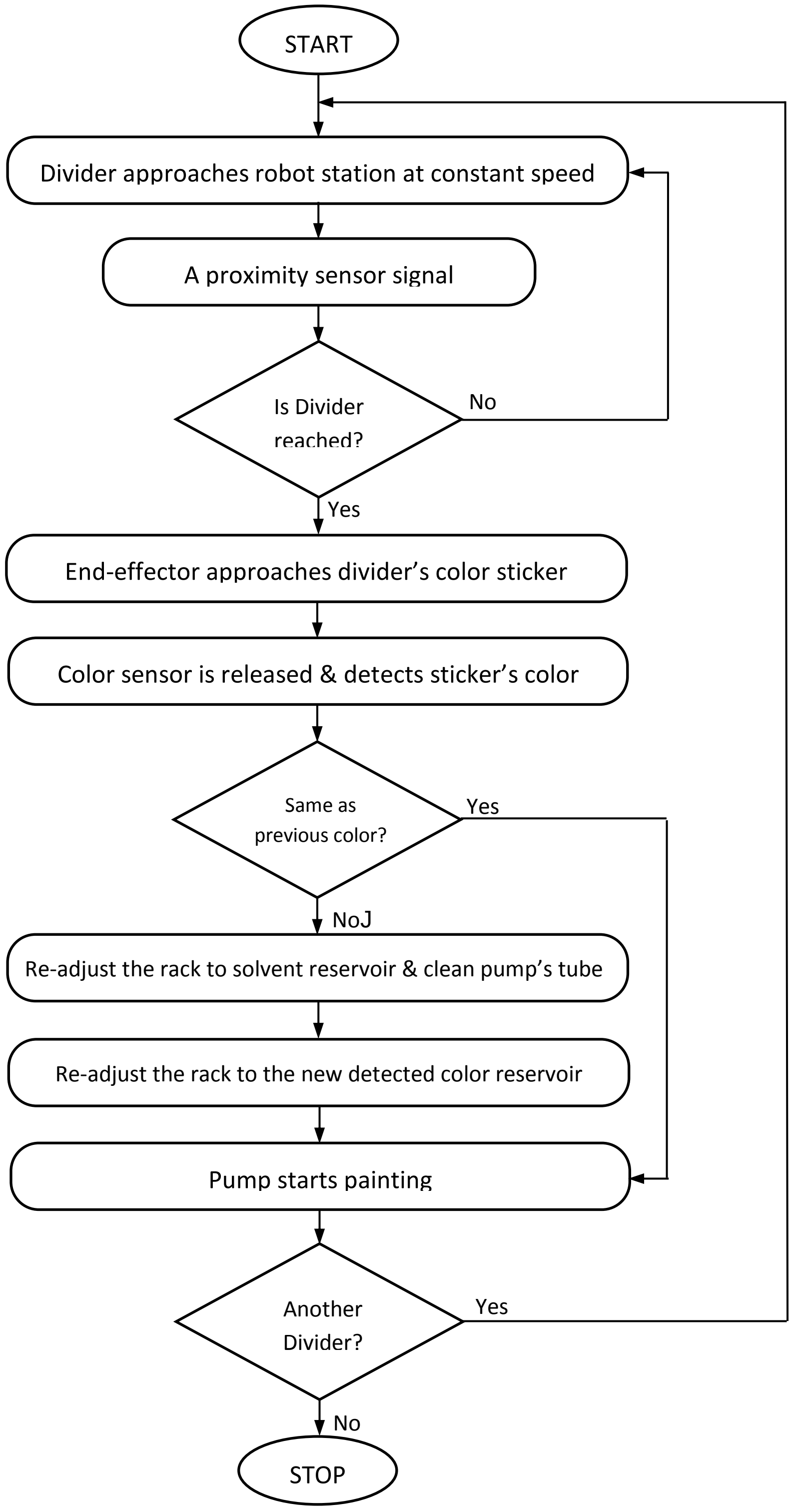

Figure 4. Flowchart of the proposed algorithm

4. Conclusions

A conceptual design for a painting robot that solves some of the basic problems in automatic painting is presented in this paper. This is the first phase of research and the second phase will be development of the prototype for this system. The integration of color sensor in this system makes it flexible and easy for implementation in different painting applications. The proposed system can be integrated to any robot with different kinematic structure or numbers of DOF and can be adjusted easily.

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