AN AUTONOMOUS ROBOTIC CELL FOR PAINTING APPLICATIONS

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ABSTRACT
Normally industrial painting robots have an articulated structure and have six degrees of freedom (DOF). This project investigated a 3 DOF robot for painting vertical objects of different colors. The proposed project utilized a SCARA type robot which has stiffness in the vertical direction and the largest workspace in industrial applications. The gripper of the robot was replaced with an end-effector which was designed to hold a color sensor and an automatic spray gun. The color sensor detects the color to be painted from a sticker pasted on the corner of the object and gives a signal to the Programmable Logic Controller (PLC) for selecting the proper container in the tank reservoir. A painting reservoir, consists of different painting tanks, was attached to the robot as a mobile unit and an electronic switch was utilized to direct the cable to the selected color based on the signal from the color sensor. The equations of motion for the SCARA robot is presented based on the Lagrange-Euler technique. The joints trajectory are designed as fifth-order polynomials to estimate the required torques and linear force for actuators. Performance analysis for accurate and homogeneous painting is provided.

KEY WORDS
Painting robot, automatic spray gun, color sensor, homogeneous, control strategy, PLC.

1. Introduction

Everyone engaged in the industry agrees that for industrial production two factors are equally important: process automation and process optimization. Automatic spray painting is such an example. Spray-painting is a crucial stage of the surface finishing of vehicles, machines etc. The demand on product with high-quality homogenous painted surfaces imposed the use of robots over humans. At the training stage, human factor is important. A skilled operator should guide the robot arm with the mounted spray-gun though the desired path. Robot, on other hand, saves the trajectories and repeats them during the mass production. The problem of this approach is that it is totally based on how operator works and reacts to the working environment. We can overcome the human factor by benefiting from the robot resources for optimizing the automatic painting process using a computer-based planning of the trajectories and the working path can be used. The optimization process is based on different criteria such as paint homogeneity, time consumption, cost and paint thickness. Many researchers applied the computer-based design and computer-based manufacturing CAD/CAM techniques for robot programming to achieve optimal spray-gun trajectories that sustain the aforementioned performance criteria [1-7].

Vivian et al. [8] developed an optimal trajectory model using nonlinear programming techniques based on Quasi-Newton method to optimize the trajectory planning on a free surface to achieve uniform deposition over painted surface and reduce wastage of coating materials. The research efforts in [9] were concentrated on the determination of the trajectory that provided the best quality of painting without consideration of painting quality as a criterion function, which is to be maximized. As a constraint they limited its lower level which gave an opportunity for proper minimization of some additional cost function. They proposed an ergonomic shape of the spray-gun’s trajectory considering minimum energy consumption and preserved painting quality. A robotic system for automating the pavement sign painting operations was developed [10]. The robotic system consisted of gantry frame equipped with transverse drive rail and automatic paint spray system. The system also included the development of font data structures that contain the shape information of pavement signs, such as Korean letters, English letters and symbols. In order to achieve the new spraying operation standards, the paint thickness function for free-form surface is proposed [12&13]. A multi-objective constraint optimization problem is formulated and parallel-perpendicular case of trajectory planning for a surface with two patches is proposed. The experimental results using a workpiece...
illustrate the feasibility and availability of the algorithm. The algorithm can be also extended to other applications.

This research is an extension to our previous work where we proposed a 3 DOF cylindrical structure robot for painting applications [11]. The main modifications are:

a. Introducing the mathematical modelling using Lagrange’s Equation and calculating the joints’ torques for given trajectories.

b. Changing the structure of the robot to SCARA type and modifying the end-effector design to use the fourth DOF offered by SCARA robot to protect the color sensor from the painting waste.

c. Replacing the rack and pinion mechanism by an electromagnetic switch for accurate selection of the painting reservoir based on signal from the color sensor. The painting reservoirs have been modified to cope with the new approach.

The main objective of this project is to design and develop a painting robotic cell for automatic industrial application. The cell consists of a SCARA robot, multi-channel color sensor, automatic spray gun, painting reservoirs, an electromagnetic switch and Programmable Logic Controller (PLC). The conceptual design, the proposed control strategy and the prototype are presented. This paper is organized as follows: Section 2 shows the mathematical modelling of the robot and investigates its kinematic analysis while section 3 illustrates the experimental setup and the design considerations. Section 4 deals with the control strategy followed by discussion and conclusions in section 5, and finally a list of references.

2. Mathematical Modelling

The proposed robotic structure here is the SCARA robot since it has 4 degrees of freedom and it has the largest work space. This is why SCARA robot has many applications especially for pick and place operations. We are going to use only 3 DOF and the fourth one which is the rotation of the end-effector will be reserved only for shifting between the color sensor and the automatic spray gun at the beginning of the painting process. It should be noted that the end-effector consists of two main elements, the color sensor and the spray gun and it will be explained in details at a later section. Figure (1) illustrates the structure of the SCARA robot and all joints axes are assigned based on Denavit-Hartenberg notations while the robot parameters are illustrated on Table (1).

![Figure (1) Configuration of SCARA robot with all axes](image)

Table 1. Robot parameters

<table>
<thead>
<tr>
<th>Link Number</th>
<th>( \theta_i )</th>
<th>( d_i )</th>
<th>( a_i )</th>
<th>( a_i )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>( \theta_1 )</td>
<td>0</td>
<td>( a_1 )</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>( \theta_2 )</td>
<td>0</td>
<td>( a_2 )</td>
<td>0</td>
</tr>
<tr>
<td>3</td>
<td>0</td>
<td>( d_3 )</td>
<td>0</td>
<td>180</td>
</tr>
</tbody>
</table>

Note that \( a_1 = a_2 = 200 \text{ mm} \) and \( d_3 = 150 \text{ mm} \). The total transformation from the end-effector to the robot base is given by:

\[
^wT_H = \begin{bmatrix}
C_2C_2 & S_1 & -C_1S_2 & a_2C_1C_2 - d_3C_1S_2 \\
S_2C_2 & -C_1 & -S_1S_2 & a_2S_1C_2 - d_3S_1S_2 \\
-S_1 & 0 & -C_2 & d_1 - a_2S_2 - d_3C_2 \\
0 & 0 & 0 & 1
\end{bmatrix}
\]  

(1)

The robot Jacobian is used to control the motion of the end-effector. The end-effector with its automatic spray gun facing the divider will move up and down with constant velocity while the vertical divider is moving horizontally on the conveyor belt at a constant speed as well. The two constant speeds will be optimized for accurate and homogeneous painting thickness. This optimization procedure minimizes the wasted painting as well. The robot Jacobian is given by:

\[
\dot{\bar{p}}_x = -a_3S_1C_2 + d_3S_1S_2 - a_2C_1S_2 - d_3C_1C_2 - C_2S_2 | \begin{align*}
\dot{\bar{p}}_y & = a_2C_1C_2 - d_3S_1S_2 - a_2S_1S_2 - d_3S_1C_2 - S_1S_2 \\
\dot{\bar{p}}_z & = 0 - a_2S_2 + d_3S_2 - C_2 | \end{align*}
\]  

(2)

Where \( \dot{\bar{p}}_x, \dot{\bar{p}}_y \) and \( \dot{\bar{p}}_z \) are the components of velocity of the end-effector in the task space and \( \dot{\theta}_1, \dot{\theta}_2 \) and \( \dot{\theta}_3 \) are the angular and linear velocities of all joints.
The equations of motion for the SCARA robot can be derived using the Lagrange-Euler Technique [14] as follows:

\[
T_1 = \left( \frac{m_2}{3} (3a_1^2 + 3a_1a_2C_2 + \frac{m_1a_1^2}{3} + m_3(a_1^2 + 2a_1a_2C_2 + a_2^2) \right) \ddot{\theta}_1 \\
+ \left( m_2a_2(a_2 + a_1C_2) + \frac{m_2a_2^2}{6} (2a_2 + 3a_1C_2 + a_2^2) \right) \ddot{\theta}_2 \\
- (m_2a_2a_3S_2 + 2m_1a_1a_2S_2) \dot{\theta}_2^2 - \frac{1}{2} (m_2a_2a_3S_2 + 2m_1a_1a_2S_2) \dddot{\theta}_2^2
\]

\[
T_2 = \left( m_2a_2(a_2 + a_1C_2) + \frac{m_2a_2^2}{6} (2a_2 + 3a_1C_2 + a_2^2) \right) \ddot{\theta}_1 + \left( \frac{m_2a_2^2}{3} + m_3a_2^2 \right) \dddot{\theta}_1 \\
+ \left( \frac{m_2a_2a_3S_2}{2} + m_1a_1a_2S_2 \right) \dddot{\theta}_1^2
\]

\[
F_3 = m_3\dddot{\theta}_3 - m_3g
\]

Where \( T_1, T_2 \) and \( F_3 \) are the torques for Joint 1 and joint 2 and the linear force for joint 3 respectively.

In order to calculate the joints’ torques, the trajectory for the three joints must be assumed in advance. The trajectory for the joints can be assumed as a third order polynomial if we want only to control the velocity. If the target is to control the acceleration as well we have to use the fifth order polynomial and the seventh order polynomial can be used if the target is to control the jerk as well. Our objective is to have an estimate for the actuator torques so we can use the suitable robot that’s why a trajectory selection based on the fifth order polynomial is desired.

The trajectory for the two rotary joints as well as the prismatic joint can be assumed as a fifth-order polynomial in the form:

\[
\theta(t) = C_0 + C_1t + C_2t^2 + C_3t^3 + C_4t^4 + C_5t^5
\]

Where the coefficients \( C_i \), \( i = 0 \rightarrow 5 \) are constants to be determined from the initial and final conditions as well as the task time. The assumed trajectory is considered as rest-to-rest motion where the joint starts from rest, increases gradually and ends at rest at the final time. The first two joints are assumed to have the same trajectory moving from 0˚ to 90˚ in 5 seconds. The third joint holding the end-effector is going to move in vertically from 0 to 0.15 m within the same time interval. The trajectories for the joints are illustrated in Figures (2 and 4) respectively. Substituting these trajectories into equations 3, 4, and 5 yields the joints torques and force as illustrated in Figures (3 and 5) respectively.

The SCARA robot should satisfy the estimated torques and force as shown in Figures.

3. Experimental Setup

The robotic cell of the implemented system consists of the
3.1 SCARA Robot Arm (Epson LS3 Robot)

The SCARA robot used in this project has four degrees of freedom (DOF), the first three is used for maneuvering while the last one is kept mainly for rotation of the end-effector so that either the color sensor or the automatic spray gun is facing the vertical divider at a time. These two elements are designed to be 90° apart. The SCARA Model is EPSON LS3-401S with 3 kg payload which will be enough to carry the color sensor and the automatic spray gun efficiently.

Six inputs and one output will be connected to the robot controller which are briefly described as follows:

Inputs:
- Y0 (Home Position)
- Y1 (Sensor Check)
- Y2 (Paint Position)
- Y3 (Paint)
- Y4 (Clean)
- Y5 (Emergency Stop)

Output:
- X6 (Robot Output)

All these pins are shown in details in Figure 15.

3.2 The End-Effector:

The end-effector is designed to accommodate the color sensor and the automatic spray gun perpendicular to each other. This is to ensure that the painting will not cover the color sensor and prevent it from detecting the correct color which in turns affects the whole process. The schematic diagram of the end-effector showing its details is shown in Figure 6. The pictures of the Felix automatic spray gun as well as the EMX1000 color sensor are shown in Figures 7 and 8, respectively.

Figure (6) Plan view of the end-effector

The pressure of the painting spray gun as well as the size of the nozzle can be adjusted for smooth thickness during the performance analysis phase.

Figure (7) The automatic spray gun

Figure (8) The color sensor

3.3 The Color Sensor:

A multi-channel color sensor is very important in this project since it will detect the required painting color from a small sticker pasted on the top right of the vertical divider. The sticker is pasted based on the required painting color and the color sensor will give a signal to the Programmable Logic Controller (PLC) to identify which painting reservoirs is going to be connected to the automatic spray gun. If two consecutive dividers have the same sticker's color, the process will be repeated smoothly.

On the other hand, if two consecutive dividers have different detected colors, the PLC will send signal to the cleanser reservoir to clean the pipes and the automatic spray gun nozzle before going to the required color. This is mainly to ensure that the color is pure and it is not polluted by the previously painted color from the last operation. EMX 1000 multi-channel color sensor is utilized and it was checked against stickers with different colors and materials to define the proper detecting distance. The color sensor's signal is going to work as a triggering signal for the painting process. Four different colors are determined from the distance of 10 cm and the results based on the confusion matrix are listed in Table 2.

In the testing procedure, following stages are tested;
- Same color stickers are sent serially.
Different color stickers are sent serially and cleaner procedure is tested.

Different color stickers are sent separately and cleaner procedure is tested.

As a result we faced only one false detection problem because of sheet position while sensor was reading blue sticker.

Table 2: COLORMAX color sensor testing

<table>
<thead>
<tr>
<th>Input Sticker Color (Real)</th>
<th>Red</th>
<th>Green</th>
<th>Blue</th>
<th>Yellow</th>
</tr>
</thead>
<tbody>
<tr>
<td># of Trials</td>
<td>15</td>
<td>15</td>
<td>15</td>
<td>15</td>
</tr>
<tr>
<td>Color</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Red</td>
<td>15</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Green</td>
<td>0</td>
<td>15</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Blue</td>
<td>0</td>
<td>0</td>
<td>14</td>
<td>0</td>
</tr>
<tr>
<td>Yellow</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>15</td>
</tr>
</tbody>
</table>

3.4 Painting Reservoir:

Four painting reservoirs and a cleanser reservoir are designed and connected to PLC through electromagnetic switch. Each reservoir has a small pump and a regulator to ensure accurate and homogeneous painting thickness. The PLC selects the proper reservoir based on the signal from the color sensor. The schematic diagram of reservoirs is shown in Figure (9). This module information from the sensors is sent digitally to the PLC card unit once it is defined. Each output is assigned a separate pin to represent different colors. (X2 to X5). The solenoid valve triggered by air sends spray paint is needed. Closing operations of the solenoid valves opening is done using six different relays.

![Figure (9) Design details of the painting reservoirs](image)

3.5 Programmable Logic Controller (PLC):

PLC is used to control the process of selecting the proper color reservoir based on the signal from the color sensor. It is also possible to use an I/O device attached to the robot controller to integrate the whole process using a single controller. The I/O was checked based on different signals and it gives excellent performance for switching from one program to another smoothly. The designed I/O device has 4 inputs and 4 outputs. During the performance analysis procedure of the whole setup, the output signals from the I/O device were not stable. So we had to go back again to our original design using PLC model DVP-SS2. The 2nd generation DVP-SS2 series slim type PLC keeps the basic sequential control functions from the DVP-SS series PLC but with faster execution speed and enhanced real-time monitoring capability.

3.6 The Conveyor Belt:

A horizontal conveyor belt which runs at constant speed is used to move the pallet containing the vertical divider. The conveyor belt has two photoelectric proximity sensor fixed in front of the robot and at the end of the stroke. As soon as the sensor detects a divider, a signal is sent to the PLC to stop the conveyor belt. The same signal will be sent also to the robot controller to start moving the end-effector with the color sensor facing the divider to detect the sticker's color and starts the painting operation. At the same time the conveyor is moving horizontally and the end-effector with the spray gun facing the divider is moving vertically up and down at a constant speed until the divider is painted. When another divider arrives the process is going to be repeated again. There is another option which we applied for smooth and accurate painting. As soon as the divider arrives in front of the robot it stops and the required color is detected and the spray gun starts painting. After finishing the painting process, a signal is sent to the conveyor belt to start moving and another divider arrives. This will help reducing the waste and improving the painting quality as well. The design details for the whole arrangement are depicted in Figure (10). The conveyor belt has a length of 2.5 m and width of 30 cm which allows designing the pallet that holds the vertical divider easily. Harmony between the horizontal speed of the conveyor belt and the vertical speed of the spray gun should exist and these constant velocities should be optimized for accurate, homogeneous and waste less paint operation.

There are two photoelectric sensors on a conveyor. These sensors are placed in front of the robot for the divider to be stopped and at the end of the conveyor belt to protect the divider from dropping to the ground.
3.7 The Flexible Magnetic Holder

A flexible magnetic holder device is designed and developed as a pallet for holding vertical and inclined dividers as well. The approach distance between the divider and the automatic spray gun can also be adjusted for smooth and homogeneous painting thickness. The body of the holder contains a three small pieces of magnets as well as adjustable physical limits to accommodate different sizes of dividers. The schematic diagram for the flexible holder with all design details is shown in Figure 11.

4. Control Strategy

The control sequence for the robotic cell can be summarized as follows:

1. The conveyor belt moves the vertical divider at a constant speed.
2. The proximity sensor detects the presence of the divider and sends signal to the PLC to stop the conveyor belt.
3. The color sensor mounted on end-effector moves towards color sticker on the divider to detect desired color. A signal will be sent to the PLC to allow the correct paint to be pumped and also to the robot controller to replace the color sensor with the spray gun facing the divider.
4. The PLC sends signal to the conveyor belt to start moving and for the robot to start moving the end-effector up and down at a constant speed as well.

As soon as the divider has been painted according to its width, another divider arrives and the same procedure is repeated. The schematic diagram for the whole robotic cell is shown in Figure 13 while the circuit board with all components is shown in Figure 14. The control strategy flowchart of the system is shown in Figure 15.
5 Discussion and Conclusion

A complete painting robot setup has been designed and developed and a performance analysis for the whole cell has been checked for evaluation. The detecting distance for the multi-channel color sensor ranges from 1.5 cm to 5 cm and the signal is strong enough to trigger the proper subroutine. The vertical stroke of the EPSON SCARA robot in this project is 150 mm and this may limit the height of the vertical divider. For longer divider, the distance between the spray gun and the vertical divider can be adjusted or longer stroke robot may be used in industry for different sizes. The cell works fine according to plan and the control strategy has been achieved successfully. This setup can be used for many automation applications easily and accurately and not only for painting the vertical dividers. It can be used for any applications that require painting different colors in a row or even different and similar colors on the same row. Also the flexible magnetic holder is another advantage since it can be used for fixing any different sizes with different orientations.

It should be noting that the painting density should be checked carefully specially when painting two different colors since the cleaning process should not affect the nozzle of the automatic spray gun. So, careful adjustment for the nozzle is required before going for actual painting process. So the pressure, the nozzle size and the painting density should be optimized for homogeneous painting.

The future work may include replacing the color sensor by a camera which allows expanding color range detection. It is also possible to add a mixing paint unit so we can adopt wide range of painting colors.

Figure (15) The flowchart for the control strategy

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