Design and Analysis of the Spray-Painting Robot for tall statues and monuments

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Abstract. The painting on tall structures, statues, monuments and buildings is a dangerous task for humans. Robotics finds its applications in operations, which are repetitive, hazardous, and dangerous. The aim of the present work is to design a manipulator for spray painting on surfaces of tall monuments, statues and structures. The robot can be installed on a crane platform for lifting and operated from the ground. A lightweight and compact design is desired that can be easily accommodated within the space of the crane. A Revolute-Revolute-Revolute-Prismatic (RRRP) type Robotic arm is developed and analysed for this application. By establishing the rigid body tree model in Robotics System Toolbox, the numerical model of direct and inverse kinematics using Homogenous Matrix Transformation is prepared in MATLAB. Using the spray patch method and offline programming method, the spray model is prepared in Solid woks to obtain trajectory waypoints. A B-spline path is generated through these waypoints. At each waypoint, joint displacement variables are calculated using an inverse kinematic model. An air-less spray gun is selected and attached with a robot. Controlled motion algorithm for spray painting operation on a circular surface were obtained with simulation results. A smooth trajectory for performing spray painting is obtained.

Keywords: Spray painting Robots; forward and inverse kinematics, trajectory generation

1. Introduction

Robotic spray-painting application are the primitive technology during the early development of robotics. There are ample amount of development is done in this field and still research is going on. Robotic spray-painting manipulators finds their application where the location of painting area is hazardous and unreachable for humans [1], [2]. Tall statues, tall buildings, monuments are the places whose painting task is dangerous for human operators. A specially designed manipulator can be mounted on a crane platform and programmed to perform spray-painting on heights[3]–[5]. It is also studied that as the gap of spray gun shape is narrow three or four jaw grippers are not useful[2], [6]. For kinematic analysis, literatures survey is made which focuses on Direct and inverse kinematics models[7]–[16]. Precise Trajectory generation methods are also studied as it is important in order to have desired spray painting [17]–[20]. This paper includes the key aspects of applying robotic painting application at height to protect human operators form worst fatal incidents, performing precision spray-painting and save resources like skill professionals, time and money. To achieve the objective of painting, a robotic manipulator follows the desired trajectory and performs spray-painting...
operation with a selected automatic airless spray-painting gun. In place of magnetic or adhesive gripper, a two-jaw gripper is selected to hold the spray-gun due to the plastic material. A specially designed two-finger gripper fitted to a spray gun neck-hole. Section 2 highlights the design aspects of manipulator, degree of freedom required for that operation and modelling of a compact, lightweight manipulator in SOLIDWORKS. Selection of sensors, actuators and material for robust and lightweight manipulator is also discussed in the section. The mathematical model for forward kinematics and inverse kinematics mathematical model is developed and discussed in section 3. Trajectory Generation and path planning for smooth spray paint are presented in section 4 and, finally, concluding remarks are given in section 5.

2. Design of Manipulator for Spray Painting

Robotic manipulator design is based on application and constraints to perform the painting operation. For performing spray-painting operation, a manipulator is required to be mounted on a platform of the crane, and then a crane is to be lifted towards the work point and manipulator fulfills painting operation. In order to fulfill the purpose a robust, compact and lightweight manipulator is required to design. It has to be compact to accommodate with in space of platform on crane. Considering complicated shapes of the area to be painted the four degrees of freedom configuration (RRRP) three revolute and one prismatic joint was designed and analysed. Configuration plays crucial role as Degrees of freedom increases instability and difficulty to control each rotational and prismatic joint through online programming method. 3-Dof RRP was first preference but in order to get desire orientation and to reach to all the intricate shape one Rotational/Twist motion is given to the base[3], [7], [8], [21]. Some important considerations should be taken while designing the robot manipulator are structure to be painted, degree of freedom, workspace, link length, types of the joint, payload, type of the platform.

2.1. Design of manipulator parts

The design of manipulator is required to be done with basic mechanical considerations. Primary component base is to be mounted on crane platform, is a revolute joint and then two revolute link and one prismatic link are designed.

a) Base: The Base is an integral part which has to be fixed on the platform. Platform dimensions is 300 mm so the base diameter is taken as 200mm and is connected with revolute joint as shown in figure 1

b) Link 1: It is connected with base through revolute joint which allows manipulator to get required position by revolving around the base as shown in the Figure 2.

c) Link 2: It is shoulder linkage of the manipulator which is connected with revolute joint between Link 1 and Link 2 with the help of revolute joint. The dimension of the Link2 is shown in the Figure 3.

d) Link 3: It is connected with Link 2 and Link 3 with the help of revolute joint and it allows getting the orientation of the spray gun at required position. The Link3 is as shown in the Figure 4.

e) Link 4: It slides at the distance d4 and reached at the required position of the gun. Figure 5 shows sliding link. The dimension of this link is 300mm.
2.2 Selection of Control System, spray-painting gun and material for the robot.

The control system is an important part of the robotics system. Selection of control system of the manipulator involves selection of actuation, sensors, vision system and method for spray painting, which involves selection of spray gun. Sensors and vision systems were selected based on the precision of painting operation. A Laser sensor and camera vision systems were selected. Spraying is the technique of painting the surface with the appropriate thickness. In automatic airless spraying the trigger is functioned with the help of the PLC. For the present application, an automatic airless spray gun is selected. Specifications of the selected spray gun are as shown in table 1.[4], [22]–[25] The selection of material for manipulator should be based on design requirements and payload to be carried with manipulator[26]. Material must possess enough strength to withstand the loads as well it should be light in weight as it is to be mounted on the crane platform. The material properties considered while selecting manipulator material were mass density, strength, machining ability and corrosion resistance. By comparing different materials on the basis of material properties Acrylic is chose as a material for manipulator for present application. It has very less mass density and good strength properties needed for a robust and light weight manipulator. After applying acrylic material to the assembly in solid works mass of whole assembly 6.1 kg obtained. The spray gun weight is 2 kg.
Design of manipulator is done considering self-weight, spray gun weight total 8.1 kg and factor of safety as 1.5.

**Table 1. Specifications of the spray gun.**

| Specifications              | Description                      |
|----------------------------|----------------------------------|
| Type of Spray-painting technique | HVLP                             |
| Weight of Spray Gun         | 2kg                              |
| Capacity of container to fill paint | 1000ml                           |
| Type of spray pattern       | Circular, horizontal, vertical   |
| Nozzle diameter             | 1.5,1.8,2.2,2.4 (mm)             |

3. Kinematic analysis of a manipulator

In this section, mathematical modeling of four-degree of freedom (RRRP) manipulator is done. Kinematic model of four degrees of freedom manipulator describes the position and orientation of the end-effector and relation between joint-link variables. Forward and inverse kinematics analysis both are required to get desired spray-painting trajectory.

3.1 Direct (or Forward) Kinematics

For mechanical structure of 4-DOF (RRRP) robot, an open kinematic chain, Denavit and Hartenberg approach is used which is known as DH notation. Literature highlighted methods to carry forward kinematic model.[3], [7], [9], [10], [12], [13], [15], [27], [28] The nomenclature used for in defining DH parameters are two link parameters ($a_i, \alpha_i$) and two joint parameters ($d_i, \theta_i$). Denavit-Hartenberg algorithm - Link Frame Assignment allows to assign frames and determine the DH-parameters for each link of a robot. With Link Frame Assignment rules, the coordinate frame is assigned to each link, the joint-link parameters ($a_i, \alpha_i, d_i, \theta_i$) is shown in the Figure 7. And D-H matrix is shown in table-2.

![Figure 7. Coordinate frame assignment for 4-DoF manipulator.](image-url)
Table 2. Joint Link parameter for 4 dof RRRP arm.

| Axis | ai | ai | di | \( \theta_i \) | Motion |
|------|----|----|----|---------------|--------|
| 1    | 0  | 90 | 200| \( \theta_1 \) | Rotation of base |
| 2    | 350| 0  | 0  | \( \theta_2 \) | Raises and lower |
| 3    | 118| 180| 5  | \( \theta_3 \) | Raises and lower |
| 4    | 0  | 0  | \( d_4 \) | 0 | Sliding motion |

With the help of D-H table and frame assignment link transformation matrices are developed as follows. The overall transformation for the endpoint of the arm is:

\[
^{0}T_4 = ^{0}T_1(\theta_1){}^{1}T_2(\theta_2){}^{2}T_3(\theta_3){}^{3}T_4(d_4)
\]

\[
\begin{bmatrix}
C_4 & 0 & S_1 & 0 \\
S_1 & 0 & -C_1 & 0 \\
0 & 1 & 0 & 200 \\
0 & 0 & 0 & 1
\end{bmatrix}
\begin{bmatrix}
C_2 & -S_2 & 0 & 350C_2 \\
S_2 & C_2 & 0 & 350S_2 \\
0 & 0 & 1 & 0 \\
0 & 0 & 0 & 1
\end{bmatrix}
\begin{bmatrix}
C_3 & -S_3 & 0 & 118C_3 \\
S_3 & C_3 & 0 & 118S_3 \\
0 & 1 & 5 & 0 \\
0 & 0 & 1 & 0
\end{bmatrix}
\begin{bmatrix}
1 & 0 & 0 & 280 \\
0 & 1 & 0 & 0 \\
0 & 1 & 0 & 0 \\
0 & 0 & 1 & 0
\end{bmatrix}
\begin{bmatrix}
C_4S_{23} & -C_4c_{23} + S_1 & 5S_1 & 398C_4c_{23} + 350C_4C_2 \\
S_4S_{23} & S_4c_{23} - C_1 & 5C_1 & 398S_4c_{23} + 350C_1C_2 \\
S_{23} & C_{23} & 0 & 398S_{23} + 350S_2 + 200 \\
0 & 0 & 0 & 1
\end{bmatrix}
\]

(1)

3.2 Inverse Kinematics

Inverse kinematics analysis involves the calculations of all joint variables when the end-effector position is known. Clamping for spray gun in specified position and orientation. To find out the solutions of inverse kinematics problem a closed form solution approach is adopted\([11], [13], [29], [30]\). The method is based on solving the unknown of joint variables with the help of algebraic equations, trigonometric identities.

\[
^{0}T_4 = ^{0}T_1{}^{1}T_2{}^{2}T_3{}^{3}T_4
\]

(2)

As Four Degrees of freedom manipulator is considered transformation matrix includes 4 joint displacement variables. The elements of the right-hand side matrix are desired orientation and positions of the clamp.

\[
\begin{bmatrix}
C_4S_{23} & -C_4c_{23} + S_1 & 5S_1 & 398C_4c_{23} + 350C_4C_2 \\
S_4S_{23} & S_4c_{23} - C_1 & 5C_1 & 398S_4c_{23} + 350C_1C_2 \\
S_{23} & C_{23} & 0 & 398S_{23} + 350S_2 + 200 \\
0 & 0 & 0 & 1
\end{bmatrix} = \begin{bmatrix}
r_{11} & r_{12} & r_{13} & r_{14} \\
r_{21} & r_{22} & r_{23} & r_{24} \\
r_{31} & r_{32} & r_{33} & r_{34} \\
0 & 0 & 0 & 1
\end{bmatrix}
\]

(3)

\[
\theta_1 = \text{Atan}(r_{11}, \ r_{21})
\]

(4)

\[
\theta_2, \ \theta_3 = \text{Atan}(r_{32}, \ r_{33})
\]

And,

\[
\theta_2 = \text{Atan}(5x, \ -r_{23}y)
\]

(5)
Now substitute the value of $\theta_2$ in Eq. (4), we get

$$\theta_3 = \text{Atan}(r_{32}, r_{31}) - \theta_2$$

Thus, by performing inverse kinematics analysis model all the joint displacement variables are obtained.

### 3.3 Workspace Analysis

The workspace analysis highlights the volume covered with the available range of manipulator. It shows the ability of the manipulator to locate the position of end effector in the space. Also, size and shape of the workspace analysis represents the work ability of the manipulator, which is very important for any robotic application. To obtain the workspace of manipulator, a range of the end effector is obtained by the angles obtained by the joint displacement variables achieved in the space coordinate system. Workspace Analysis is carried out with the help of Monte Carlo method. For solving the mathematical equations, it requires to establish a probability model, by giving certain boundary conditions of random variables. As per required application an algorithm is developed with the help of Monte Carlo method is done in MATLAB. After calculation of Direct kinematics of the arm the solution from the Equation- 3.5 is as below:

$$X = d_4 a_3 \cos (\theta_1) \cos (\theta_2 + \theta_3) + L_2 \cos(\theta_1) \cos(\theta_2);$$

$$Y = (d_4 + a_3) \sin(\theta_1) \cos (\theta_2 + \theta_3) + L_2 \sin(\theta_1) \cos(\theta_2);$$

$$Z = (L_1+L_2) \sin(\theta_2) + d_4 a_3 \sin (\theta_2 + \theta_3);$$

Constrains of joint displacement variables are considered as,

$$-90^\circ < \theta_1 < 180^\circ, \quad 90^\circ < \theta_2 < 180^\circ, \quad 90^\circ < \theta_3 < 180^\circ, \quad 0 < d_4 < 280;$$

(All the values of revolute joints are in degrees while prismatic joint is in mm). Results of generated by code are plotted in 3D space and the workspace analysis is obtained, that results as dome like structure with length of reach is 750mm.

![Figure 8. Workspace Analysis of RRRP configuration.](image)

### 4. Trajectory Planning

Trajectory required performing desired operation of painting on the monument or statue a path-planning algorithm is developed. Considering shape to be painted as circular a Rigid Body Tree model, trajectory model, inverse kinematics model code is generated in MATLAB. The main aim of trajectory planning is to achieve a smooth and jerk free motion of the manipulator. In trajectory planning required motion of the manipulator as function of time sequence, are generated by interpolating the appropriate path through polynomial function[20], [31]. For smooth jerk free performance, B-spline Polynomial Trajectory is considered. Table 3 and 4 shows the waypoints that were given as an input for the motion of the robot.
The robot model known as rigidBodyTree in the Robotics System Toolbox is prepared in MATLAB by writing the code. In code detail, description of each link-joint is described with the boundary constraints of joint displacement variables as the robotic manipulator drawn in CAD model.

4.1 Robot Path Generation

After generation of way-points the path is decided, the code is prepared with the help of Robotics System Toolbox in MATLAB. For generation of trajectory, it requires to prepare the path generation to follow the trajectory and output obtained. Figure 9: Waypoints that are obtained by giving boundary conditions in parametric scheme. Figure 10: For painting of circular object, trajectory obtained in MATLAB Robotics System Toolbox. Figure 11: Through each point the spray gun will spray and each point are covered through mathematical expressions, where all the way-points are traced.

![Figure 9. Waypoints plotted in MATLAB.](image-url)
For the Robot Trajectory Generation, it uses joint space technique. Trajectory is generated in Robotics System Toolbox. The output as paint patches obtained is plotted as shown in the Figure 11.

5. Conclusion

Performing spray painting on tall statues, monuments and structures are difficult and dangerous task for human operators if done manually. Spray-painting robots mounted on crane platform with desired motion and trajectory controls can perform the painting on tall statues properly. In order to fulfill the desired objective a 4 degrees of freedom robotic manipulator is designed based on the criteria of
robust and light weight structure. Selection of actuators, sensors and spray gun is made in this work. Mathematical model of Forward and inverse kinematic were developed and utilized for obtaining smooth trajectory of spray gun. A precise trajectory profile and spray patches were obtained covering all the considered way points on the selected shape.

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