Workspace Analysis of Spray Painting Robot with Two Working Modes for Large Ship Blocks in Ship Manufacturing

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Abstract. Spray painting is crucial in the process of shipbuilding and runs through the whole process of shipbuilding. In order to obtain the good coating quality during the painting process, gantry type painting robot could be used because of its resource-saving and environment-friendly characteristics. Based on the structural parameters of the spray painting manipulator with 3DOF (Degree of freedom) gantry, the kinematic model of the painting robot system can be established. From the perspective of the two commonly working modes, namely 3P3R robot structure and the 3P6R redundant robot structure, their spraying workspace are analyzed. The result shows that the workspace volume of the 3P6R robot is much larger than that of the 3P3R robot. However, the inverse kinematics solution of 3P3R robot has analytical solution, which makes the control accurate and easy to use, and through the simulation, we can give the theoretical basis for the engineering.

1. Introduction

The shipbuilding process entails processing and assembling variously sized blocks [1]. Spray painting is significant in the ship processing, which have played an important role in protection and decoration for the large ship blocks. The high risk operation mode of ship blocks painting relying on a large number of manual operation is not in line with the concept of green environmental protection [2]. The application of robots in ship blocks spray paint will greatly improve the occupational health of the construction personnel [3], the coating quality [4], and the construction efficiency [5].

Both the processing and assembling of blocks require large working areas. The research on the spray painting robot adapting to the characteristics of the ship blocks need to be studied. A reachable workspace is a position set that an end-effector can reach without considering orientation.

Publications dealing with this topic are considered in this research. There has been much research to analyze or optimize the workspace of serial manipulators which developed to be used in ship manufacturing [6-7]. Workspace analysis of the serial manipulator mounted on the hexapod robotic platform for different base locations was carried out while the legged platform was in stance [8]. Antonov [9] built the workspace of 5DOF hybrid manipulator and determined its shape, dimensions, et al, which served as a basis for the further analysis of velocities and accelerations. Simulations were conducted with the end-effector to investigate the reachable workspace by Azlan [10].

The workspace analysis of parallel robot could provide reference for workspace analysis method and application of spray painting robot. Amir [11] presented an analytical approach for the dimensional synthesis of the 3DOF Delta parallel robot for a prescribed workspace. Zhang [12] showed that the surgical demand workspace is located inside the reachable workspace of the 7DOF
redundant mechanism and the joint locking of the manipulator is reliable. A preliminary virtual design of the mechanism was presented and the workspace analysis is performed by Leal-Naranjo [13].

A robot system composed of a general 6DOF manipulator mounted on a 3DOF gantry can be used to spray the large ship blocks. The 9DOF spraying robot system could be worked at 3P3R or 3P6R mode. The former is common in industry, the latter makes the robot system more flexible and easy to avoid singular configurations, while the former is easy to control and plan. At present, there is almost no quantitative evaluation and analysis in the literature for which mode is more suitable. As one of the most important indexes, workspace can be used to measure which way the system works most reliably.

2. Structure of the spray painting robot

As the geometry of the ship blocks, “Mobile & Operation” robot system would be the good choice for the painting of the ship blocks surface. Prototype of the spray painting robot system are shown in Figure 1. 3DOF gantry can be considered as three prismatic joints, $J_1$, $J_2$, $J_3$, in that it allows translational (or rectilinear) motion along the direction of the joint axis.

![Figure 1. Prototype of the robot system in Solidworks](image1)

The painting robot consists of 3DOF gantry and a painting manipulator (Stäubli RX160L) which has six revolute joints, $J_4$, $J_5$, $J_6$, $J_7$, $J_8$, $J_9$. The model and relevant parameters of painting manipulator are shown in Figure 2. Base coordinate frames $x_0y_0z_0$, robot coordinate frames and relative parameters are shown in Figure 3, which describe the topological and geometric relationship between joints so that the kinematic model of spray painting robot could be established.

![Figure 2. Stäubli RX160L parameters](image2)

![Figure 3. Coordinate frames of the robot](image3)

3. Kinematic analysis of the robot

3.1. Kinematics Model of the Robot

According to the relationship between the structural parameters and topological structure of the spray painting robot system joints, the Denavit-Hartenberg (DH) parameters of the robot system are given in Table 1. $x$, $y$, and $z$ stand for the input translations of the 3DOF gantry, $\theta_4$, $\theta_5$, $\theta_6$, $\theta_7$, $\theta_8$, $\theta_9$ stand for the input angles of the six revolute joints of the manipulator. The structural parameters of the spray...
painting robot system are as follows, $a_0=20900.00\text{mm}$, $a_4=150.00\text{mm}$, $a_5=825.00\text{mm}$, $d_4=997.70\text{mm}$, $d_7=925.00\text{mm}$, $d_9=109.00\text{mm}$.

Table 1. DH parameters of the robot

| Link $i$ | $a_{i-1}$ | $a_i$ | $d_i$ | $\theta_i$ |
|----------|-----------|-------|-------|------------|
| 1        | $a_0$     | 0     | $x+798.07\text{mm}$ | 0          |
| 2        | 0         | 0     | $y+499.80\text{mm}$ | 0          |
| 3        | 0         | $90^\circ$ | $z+1228.12\text{mm}$ | $90^\circ$ |
| 4        | 0         | $-90^\circ$ | $d_4$ | $\theta_2-90^\circ$ |
| 5        | $a_4$     | $-90^\circ$ | 0 | $\theta_2-90^\circ$ |
| 6        | $a_5$     | 0     | 0     | $\theta_6-90^\circ$ |
| 7        | 0         | $-90^\circ$ | $d_7$ | $\theta_7$ |
| 8        | 0         | $90^\circ$ | 0     | $\theta_8$ |
| 9        | 0         | $-90^\circ$ | $d_9$ | $\theta_9$ |

The input of prismatic joints and revolute joints are variables. The homogeneous transformation matrix which is given in equation (1) represents the final position and orientation of end effector with respect to the base coordinate system.

$$
T_i^{-1}(\theta_i) = \begin{bmatrix}
    c\theta_i & -s\theta_i & 0 & a_i \\
    s\theta_i \alpha & c\theta_i \alpha & -s\alpha & -d_i s\alpha_i \\
    s\theta_i s\alpha & c\theta_i s\alpha & c\theta_i & d_i c\alpha_i \\
    0 & 0 & 0 & 1 \\
\end{bmatrix}
$$

Where c denotes cos function, s denotes sin function.

The synthesis transformation matrix is given in (2).

$$
T = \prod_{i=1}^{9}(T_i^{-1}(\theta_i)) = T_1^0 \times T_2^{-1} \times T_3^{-1} \times T_4 \times T_5 \times T_6 \times T_7 \times T_8 \times T_9
$$

The position and orientation matrix of the spray painting robot end effector is given in (3).

$$
T = \begin{bmatrix}
    n_x & o_x & a_x & p_x \\
    n_y & o_y & a_y & p_y \\
    n_z & o_z & a_z & p_z \\
    0 & 0 & 0 & 1 \\
\end{bmatrix}
$$

Where $(p_x, p_y, p_z)$ represents the position of robot end effector. $(n_x, n_y, n_z)$, $(o_x, o_y, o_z)$, $(a_x, a_y, a_z)$ represent the orientation vector included normal vector, orientation vector and approach vector of robot end effector, respectively.

3.2. Kinematic Model of Spray Painting Robot with 3P3R Working mode

In actual painting process, $J_4$, $J_5$, $J_6$ of spray painting robot system could be fixed, and the robot system would work at another mode usually. In this circumstance, robot coordinate frames and relative parameters are shown in Figure 4. The DH parameters of the robot system are given in Table 2.
Table 2. Real solutions of the robot

| Link $i$ | $a_{i0}$ | $a_{i1}$ | $d_i$ | $\theta_i$ |
|----------|---------|---------|-------|---------|
| 1        | $a_0$   | 0       | $x'$ +798.07 | 0       |
| 2        | 0       | 0       | $y'$ +499.80 | 0       |
| 3        | 0       | 90°     | $z'$ +1228.12 | 90°     |
| 4        | 0       | -90°    | $d_k'$       | $90°+\theta_k'$ |
| 5        | 0       | 90°     | 0           | $\theta_k'$ |
| 6        | 0       | -90°    | $d_0$       | $\theta_k'$ |

The structural parameters of the spray painting robot system are as follows, $a_0' =20750.00\text{mm}$, $d_4' =2747.70\text{mm}$, $d_6 =109.00\text{mm}$. Use parameters above and equation (2)-(3), the real forward solution of the spray painting robot with 3P3R could be obtained, which is the basis for workspace analysis.

4. Workspace analysis

4.1. Workspace of Painting Robot with 3P3R Working Mode

According to the kinematic model of the spray painting robot system, the range of each joint motion is set as follows: $x' \in [-30648.07\text{mm}, -948.07\text{mm}], y' \in [1920.20\text{mm}, 3014.20\text{mm}], z' \in [9218.88\text{mm}, 10093.88\text{mm}], \theta_2' \in [-360°, 180°], \theta_3' \in [-105°, 120°], \theta_4' \in [-270°, 270°]$. The range of prismatic joints is set in accordance with the path on the large ship block to be sprayed, as shown in the red circle in Figure 5. By Monte Carlo method, the workspace of the robot could be calculated.

![Figure 5. Path of spray painting robot](image)

The experiments are conducted on a workstation with Intel Xeon 3.70GHz processor. When three prismatic joints remain unchanged, the workspace $\alpha$ of the spray painting robot working mode is shown in Figure 6. As the movement of 3DOF manipulator is very limited, the size of it would be smaller than that of the 6DOF manipulator. Entire workspace $\beta$ of the spray painting robot with 3P3R working mode is shown in Figure 7. Its shape is close to a cuboid, and its size is much larger than that of the 3DOF manipulator. The influence of the movement of 3DOF gantry on the workspace of the robot is much greater than that of the 3DOF rotate axis movement of the manipulator.

![Figure 6. $\alpha$ of 3DOF manipulator](image)  ![Figure 7. $\beta$ of the robot with 3P3R working mode](image)

4.2. Workspace of Painting Robot with 3P6R Working Mode

Each joint motion of the spray painting robot system with 3P6R working mode is set as follows. The range of joints $x, y, z$ are same with the range of joints $x', y', z'$. $\theta_4 \in [-70°, 250°], \theta_5 \in [-47.5°, 227.5°], \theta_6 \in [-60°, 240°], \theta_7 \in [-270°, 270°], \theta_8 \in [-105°, 120°], \theta_9 \in [-270°, 270°]$.

The workspace $\gamma$ of the spray painting robot with 3P6R working mode is shown in Figure 8 when three prismatic joints remain unchanged, which is the traditional 6DOF manipulator workspace. The
whole workspace $\delta$ of the spray painting robot with 3P6R working mode is shown in Figure 9. With the increase of the influence of the rotation of the manipulator, the outer edge of the whole workspace becomes rounded, and the size of the workspace is larger than the workspace of the spray painting robot with 3P3R working mode. Therefore, this 9DOF robot system is very suitable for the spray painting of large ship blocks. However, the size of the workspace of the robot system at two working modes still needs to be further accurately solved and analyzed.

![Figure 8. $\gamma$ of 6DOF manipulator](image1)

![Figure 9. $\delta$ of the robot with 3P6R working mode](image2)

4.3. Workspace Comparision
Since the workspace of the robot system is composed of a series of scattered points, we need to extract the boundary points of the three dimensional workspace first, and then calculate the volume of the space enclosed by the boundary points. In this paper, the boundary points of the working space are connected by triangular pieces and form the outer surface. Boundary points and outer surface of spray painting robot workspace $\beta$, $\delta$ are shown in Figure 10 and Figure 11.

![Figure 10. Boundary points and outer surface of $\beta$](image3)

![Figure 11. Boundary points and outer surface of $\delta$](image4)

In order to ensure that the volume calculation results are as accurate as possible, 8 sets of calculations are performed on the spray painting robot with 3P6R working mode and 3P3R working mode as shown in table 3. Their coefficient of variation are obtained, which are 0.0090 and 0.0114 respectively. The fluctuations are very small, indicating that the volume calculation results could be adopted. Then the average value of workspace of robot with two different working modes are calculated. The volume of the workspace of robot with 3P6R working mode is 13.1145 times that of robot with 3P3R working mode, which is convenient for the spraying of large ship blocks. As part of path is considered, the effect of rotate joints range is much greater than that of prismatic joints range. The effect will decrease as more paths are considered.

| No. | 3P6R($\text{mm}^3$) | 3P3R($\text{mm}^3$) |
|-----|------------------|------------------|
| 1   | $4.9931 \times 10^{11}$ | $3.5354 \times 10^{10}$ |
| 2   | $4.9784 \times 10^{11}$ | $3.4684 \times 10^{10}$ |
| 3   | $5.0112 \times 10^{11}$ | $3.4929 \times 10^{10}$ |
| 4   | $4.9690 \times 10^{11}$ | $3.5162 \times 10^{10}$ |
| 5   | $4.9197 \times 10^{11}$ | $3.5217 \times 10^{10}$ |
| 6   | $4.9362 \times 10^{11}$ | $3.5795 \times 10^{10}$ |
| 7   | $5.0645 \times 10^{11}$ | $3.5360 \times 10^{10}$ |
| 8   | $4.9853 \times 10^{11}$ | $3.5886 \times 10^{10}$ |
5. Conclusion
In this paper, the kinematics model of spray painting robot is established, and its kinematics equation is calculated. The effectiveness of the kinematics model of the robot is proved by numerical examples. Based on the kinematics model, the workspace of the spray painting robot working at two different modes is calculated and compared. Although spray painting robot with 3P3R working mode is easier to control than spray painting robot with 3P6R working mode, the results show that spray painting robot with 3P6R working mode has a larger working space than spray painting robot with 3P3R working mode, and could better meet the spray painting needs of large ship blocks. To enhance the applicability of the spray painting robot, dynamics and control precision of the robot are planned as the future work of this research.

Acknowledgment
This work is supported by Program of Ministry of Industry and Information Technology of the People’s Republic of China (MC-201906-Z01).

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