Innovative Painting Robotic Cell for Industrial Applications

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Abstract

Normally industrial painting robots have an articulated structure and have six degrees of freedom (DOF). This project investigates a 3 DOF robot for painting vertical objects of different colors. The proposed project utilizes a SCARA type robot which has stiffness in the vertical direction and the largest workspace in industrial applications. The gripper of the robot is replaced with an end effector which is 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, is attached to the robot as a mobile unit and an electronic switch is utilized to direct the cable to the selected color based on the signal from the color sensor.
A mathematical kinematical model for the SCARA robot is presented. Analysis of the painting parameters for accurate and homogeneous painting is provided.

Key words: Painting robot, 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 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] researchers 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.

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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. There 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.
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:

- 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.
- 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 paper 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 as well as the proposed control strategy is presented. The paper is organized as follows: Section 2 shows the mathematical modeling 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.

2. Mathematical Formulation

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.

Table 1. Robot Parameters

Link Number	θ_i	d_i	a_i	α_i
1	θ_1	0	a_1	0
2	θ_2	0	a_2	0
3	0	d_3	0	180

Note that $a_1 = a_2 = 200\,mm$ and $d_3 = 150\,mm$. The total transformation from the end-effector to the robot base is given by:

$$
{}^{0}T_{H} = \begin{bmatrix} C_1C_2 & S_1 & -C_1S_2 & a_2C_1C_2 - d_3C_1S_2 \\ S_1C_2 & -C_1 & -S_1S_2 & a_2S_1C_2 - d_3S_1S_2 \\ -S_1 & 0 & -C_2 & d_1 - a_2S_2 - d_3C_2 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (1)
$$

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 constants speed will be optimized for accurate and homogeneous painting thickness. This optimization ensures accurate and homogeneous painting thickness and minimizes the wasted painting as well. The robot Jacobian is given by:

$$
\begin{bmatrix} \dot{P}_x \\ \dot{P}_y \\ \dot{P}_z \end{bmatrix} = \underbrace{\begin{bmatrix} -a_2S_1C_2 + d_3S_1S_2 & -a_2C_1S_2 - d_3C_1C_2 & -C_1S_2 \\ a_2C_1C_2 - d_3C_1S_2 & -a_2S_1S_2 - d_3S_1C_2 & -S_1S_2 \\ 0 & -a_2C_2 + d_3S_2 & -C_2 \end{bmatrix}}_{Jacobian} \begin{bmatrix} \dot{\theta}_1 \\ \dot{\theta}_2 \\ \dot{d}_3 \end{bmatrix} \quad (2)
$$

Where $\dot{P}_x, \dot{P}_y$ and $\dot{P}_z$ are the components of velocity of the end-effector in the task space and $\dot{\theta}_1, \dot{\theta}_2$ and $\dot{d}_3$ are the angular and linear velocities of all joints.

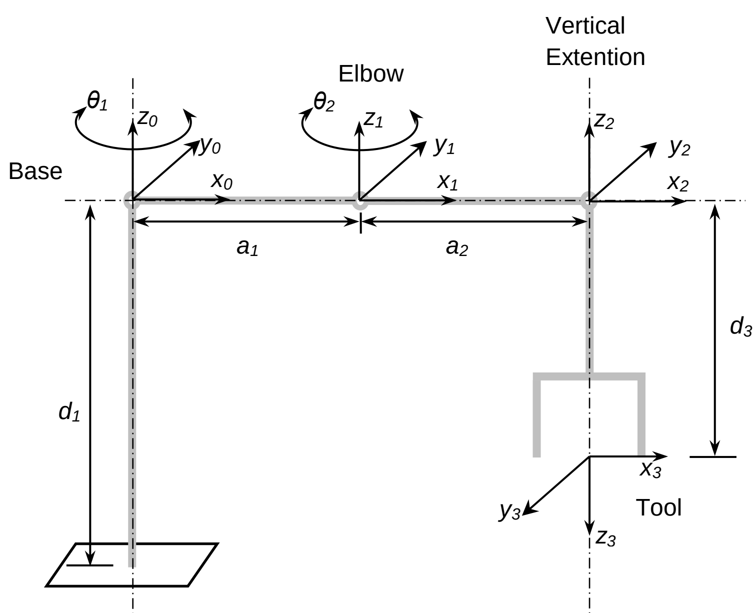

Figure 1. Configuration of SCARA robot with all axes

3. Experimental Setup

The robotic cell consists of the following elements:

3.1 SCARA Robot Arm: with 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 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.

3.2 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 2.

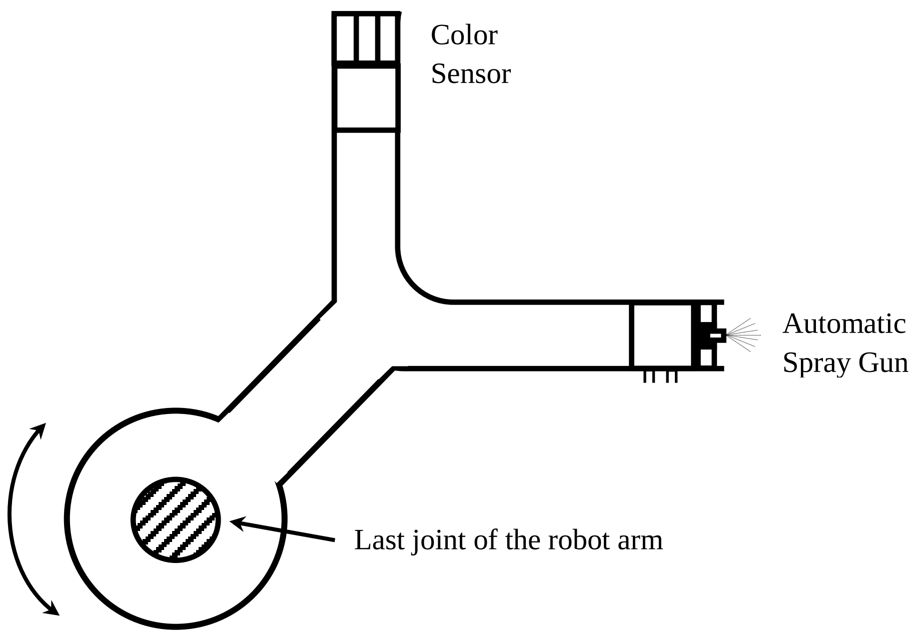

Figure 2. Plan view of the end-Effector

3.3 The Color Sensor: with multi-channel 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 tainted 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.

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. Details of reservoirs are shown in Figure 3.

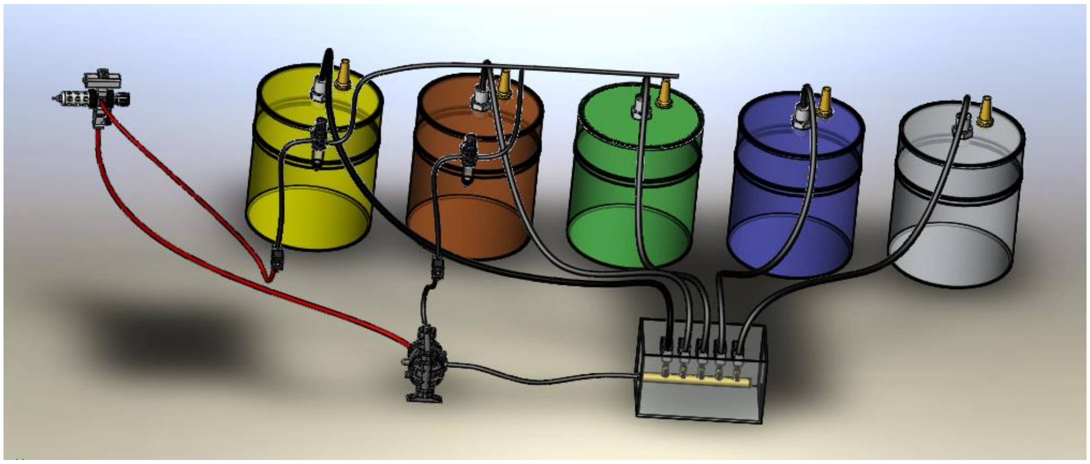

Figure 3. Design details of the painting reservoirs

3.5 Programmable Logic Controller (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.

3.6 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 a proximity sensor fixed in front of the robot and 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. A schematic diagram for the whole arrangement is depicted in Figure 4.

4. Control Strategy

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

- The conveyor belt moves the vertical divider at a constant speed.
- The proximity sensor detects the presence of the divider and sends signal to the PLC to stop the conveyor belt.
- 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.
- 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 pained according to its width, another divider arrives and the

same procedure is repeated. A flowchart describing the control strategy is shown in Figure 5.

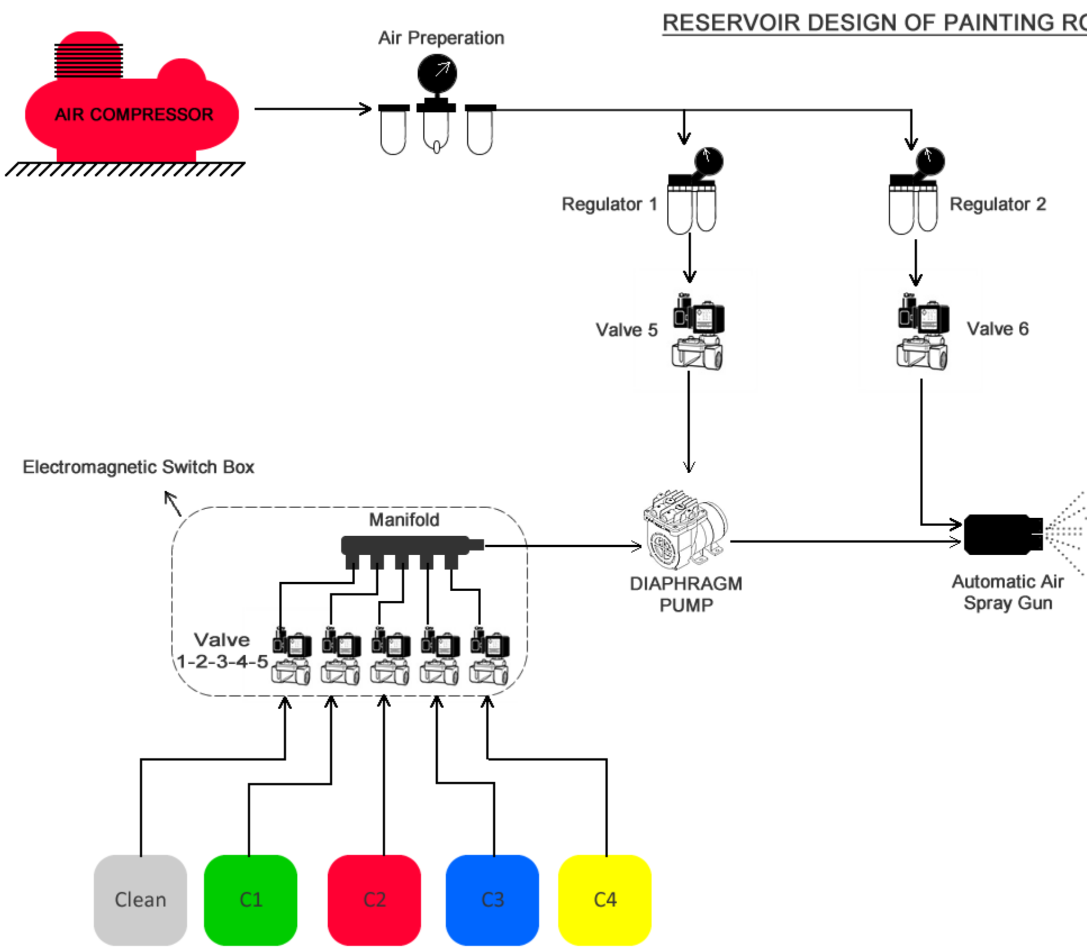

Figure 4. A schematic diagram for the whole robotic cell

5. Discussion and Conclusions

So far, the robot I/O device attached to the robot controller and the color sensor are checked and a code for integration among these elements is written and executed successfully. 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. We are in the process of combining the whole system together and the performance of the robotic cell will be examined and analyzed.

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 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.

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.

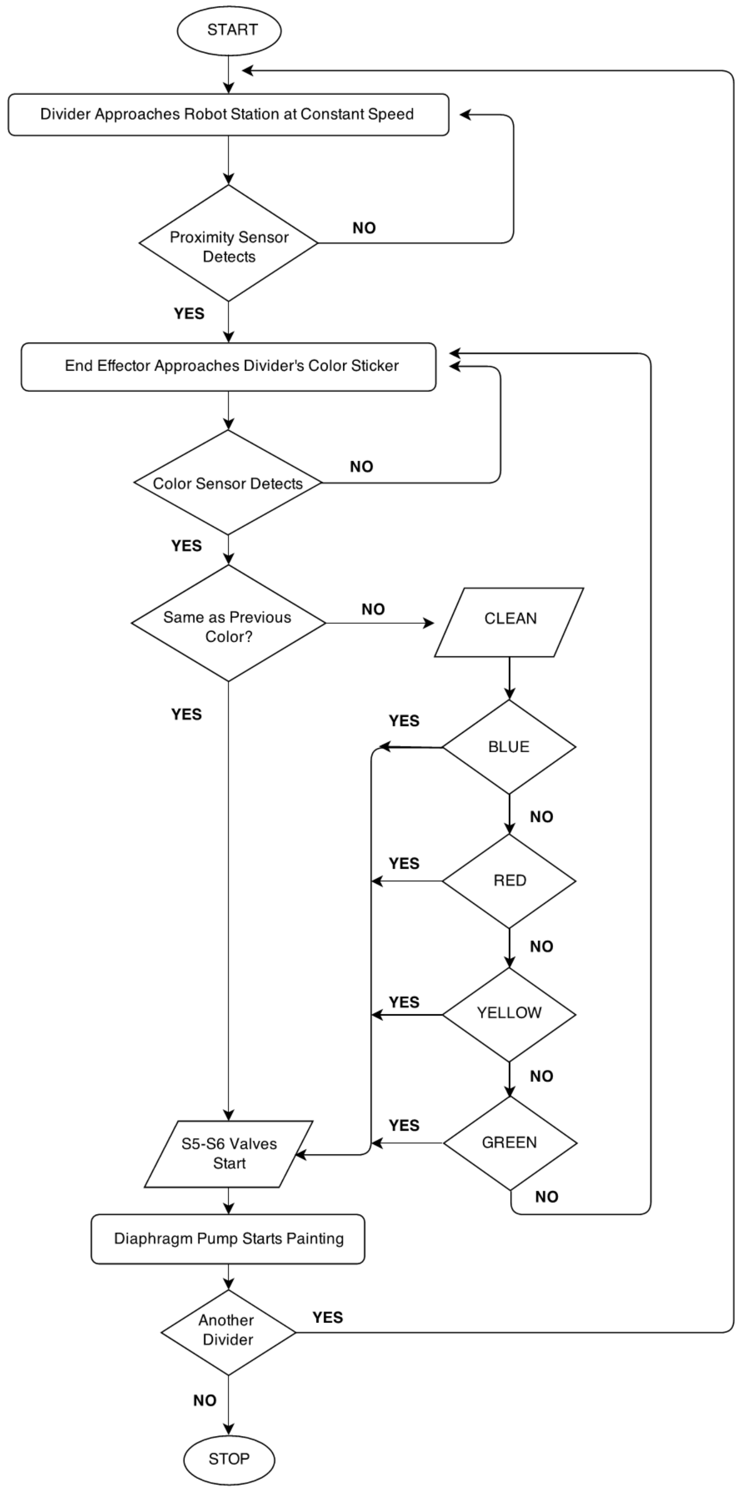

Figure 5. Flowchart of the control strategy

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References

[1] Li, Xiongzi; Landsnes, Oeyvind A.; Chen, Heping; Sudarshan M-V; Fuhlbrigge, Thomas A.; Rege, Mary-Ann, "Automatic trajectory generation for robotic painting application", 41st International Symposium on Robotics and 6th German Conference on Robotics (ROBOTIK) , pp.1-6, 7-9 June 2010

[2] Heping Chen; Fuhlbrigge, T.; Xiongzi Li, "Automated industrial robot path planning for spray painting process: A review," IEEE International Conference on Automation Science and Engineering, CASE 2008 , pp.522-527, 23-26 Aug. 2008

[3] Zhou Bo; Zhang Xi; MengZhengda; Dai Xianzhong, "Off-line programming system of industrial robot for spraying manufacturing optimization," 33rdChinese Control Conference (CCC), pp. 8495-8500, 28-30 July 2014.

[4] Gasparetto, Alessandro; Vidoni, Renato; Pillan, Daniele; Saccavini, Ennio, "Automatic path and trajectory planning for robotic spray painting", Proceedings of 7th German Conference on Robotics ROBOTIK 2012, pp.1-6, 21-22 May 2012.

[5] Heping Chen; Weihua Sheng; Ning Xi; Mumin Song; Yifan Chen, "Automated robot trajectory planning for spray painting of free-form surfaces in automotive manufacturing," Proceedings of the IEEE International Conference on Robotics and Automation. ICRA '02. , vol. 1, pp.450-455, 2002

[6] Weihua Sheng; Ning Xi; Mumin Song; Yifan Chen; Macneille, P., "Automated CAD-guided robot path planning for spray painting of compound surfaces," Proceedings of 2000 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS 2000), vol. 3, pp.1918-1923, 2000.

[7] Heping Chen, Weihua Sheng, Ning Xi, Mumin Song, Yifan Chen, "CAD-based automated robot trajectory planning for spray painting of free-form surfaces", Industrial Robot: An International Journal vol. 29, no. 5, pp. 426-433, 2002.

[8] Vivian W.Y. Tam, X.D. Diao, S.X. Zeng,"Development of an optimal trajectory model for spray painting on a free surface". Computers & Industrial Engineering, vol. 57, no. 1, pp. 209-216, 2009.

[9] VeljkoPotkonjak, Goran S. Đorđević, Dragan Kostić, Milan Rašić, "Dynamics of anthropomorphic painting robot: Quality analysis and cost reduction", Robotics and Autonomous Systems, vol. 32, no. 1, pp. 17-38, 2000.

[10] Daehie Hong, Woo-Chang Lee, Baeksuk Chu, Tae-Hyung Kim, Woo Chun Choi Gantry,"Robot with extended workspace for pavement sign painting operations", Journal of Mechanical Science and Technology, vol. 19, no. 6, pp. 1268-1279, 2005.

[11] Atef A. Ata, Alaa Eleyan (2014), "Design of a Painting Robotic Cell for Industrial Applications" The 2ndInternational Conference on Innovative Technology in Engineering and Science, ISITES'14, 18-20 June 2014, Karabuk, Turkey, pp. 1168-1175.