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Spray Painting of a General Three-Dimensional Surface

Prof.Aziza Zaki Dr.Mona Eskander
Electronics Research Institute
National Research Center
Tahrir Street,Dokki
Cairo,Egypt
Fax:202-3351631
e-mail:eskander@eri.sci.eg

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ABSTRACT

An economic automatic system for spray painting of a general three dimensional surface is described. The spray gun is mounted on the wrist of a six degree of freedom (6 DOF) industrial robot. The system functions by the method of camera space manipulation, using two CCD cameras to scan the surface dimensions off-line, and store them in a supervisory computer in the form of nodes. An inverse kinematic program is developed and stored in the computer to calculate the trajectories of the six joints corresponding to the nodes on the surface, to acquire the correct position and orientation of the spray nozzle. The values of the joint angles are fed to the controllers of the joint motors every time interval, depending on the number of nodes and the required spray painting rate.

Sensors are used to inform the computer with the surface presence well as of the home position and end of trajectory. The computer also receives sensory data from the motor controllers as spray painting of the workpiece is accomplished. The position and velocity trajectories of two surfaces with different geometries (rectangular and hemispherical) are calculated using the proposed algorithm, and plotted for each of the six joints angles.

1.INTRODUCTION

Spray painting is used in a variety of industrial applications, e.g. home appliances, lamp holders ...etc. Applying automation in this industrial sector is very important from the view point of safety of the human operators, as well as precision of the painting process. The tolerance between the nozzle and the surface varies according to the type of coating applied, and might reach few millimeters. It is quite difficult for a human operator to achieve this level of precision in a consistent fashion.

Surfaces receiving spray painting have different geometry and sizes. When the batch size of the painted surface is small, the time and expenses involved in the trajectory teaching process accounts for a large percentage of the overall cost of the part. This fact coupled with the stiff tolerance requirements for obtaining successful spray painting, make the process of teaching the robot a suitable trajectory difficult and time consuming. In order to reduce the time and expenses involved in spray painting, a vision – guided robotic system is developed. The system provides the necessary level of precision in positioning and orienting the robotic sprayer relative to a surface of unknown geometry, arbiterarily located in the workspace of the robot. It also substantially reduces the time required to teach the robot a new trajectory for different surface geometry. Hence, a three-dimensional surface is painted without requiring a prior description of its geometry.

The proposed system consists of a six degree of freedom articulated robot with spherical wrist, two CCD cameras, and a computer equipped with the motion control boards necessary to communicate with all of the system hardware. The surface dimensions, which should be convex or plane, defined by the cameras, are supplied to the computer before starting painting. It calculates the six joints' angles corresponding to defined points on the painted surface, using a composed geometrical oriented inverse kinematic program. The values of the joint angles are fed to the joint motors controllers to achieve the required motor position.

Previous work in spray painting used trajectory planning algorithms [1,2], which is tedious. Three cameras were employed in [3], leading to a more expensive system. Also, to demonstrate the proposed system clearly, position and velocity trajectories, utilizing the proposed algorithm, are plotted for a rectangular surface, and a hemispherical surface.

2.SYSTEM DESCRIPTION

The main equipment involved in the proposed spray painting system are briefly described as follows:

(i) The six DOF robot consists of the articulated manipulator shown in Fig.(1), with the spherical wrist shown in Fig.(2), are placed vertically. The robot is controlled in real time from an external computer via a serial computer link.

(ii) The concentric spraying nozzle is attached to the tip of the robot wrist

(iii) Two charge coupled device (CCD) cameras with interfacing and initial image processing equipment to link the vision system with the robot control system

(iv) Six joint actuators with their controllers. The actuators are permanent magnet motors with different ratings according to the torque applied to each joint (iv) Six joint actuators with their controllers. The actuators are permanent magnet motors with different ratings according to the torque applied to each joint

(v) The control system computer (IBM compatible) with interfaces to vision system, and joint actuators controllers.

3.MODES OF OPERATION

Two operating modes are employed in the spray painting process:

A Teaching mode

Off line teaching is employed to prevent damaging the CCD cameras during painting. In this operating mode, the first step is to identify the surface to be sprayed by means of the cameras. The cameras are placed such that their axes are perpendicular. Each camera takes a view of the surface from a different side. Two constraints are employed in such vision system, i.e. the surface to be painted is symmetrical, and the surface could be convex or plane but not concave. By means of a developed software program loaded in the main computer, the three dimensions of the surface are concluded, and saved in the computer. Applying a graphical user interface program running in the windows environment., and with an operator- set spray painting speed relevant to geometry of the painted surface, the operator establishes a set of joint poses (nodes), hence creating the trajectory for the painting process. To ensure homogenity of the spray layer, the painting paths are parallel straight line segments for plane surfaces, while curved surfaces are approximated by several planes. Thus the number and locations of the nodes on the painted surface at which the joint angles are to be calculated are determined off line. The operator can also design the distance separating the spraying nozzle from the surface. As the joint poses are now determined, the computer calculates the values of the six joints; angles at each node using a developed inverse kinematic program loaded in its memory. These values are organized as a look–up table to be fed to the joints' motors controllers during the operating mode.

(2nd) Operating Mode

The cameras are removed from the spray painting area. Proximity sensors are used to inform the computer that the surface to be painted is in its place to start the painting process. The computer then issues commands to the joints' controllers via serial communication ports, to adjust the joints' angles to values corresponding to the predetermined nodes. The computer receives responses from these controllers as the command is accomplished, to supply the controllers with the values of the angles corresponding to the following node. The time taken to adjust the angles at each node, and inform the computer with it, is consistent with the joints' motors inertia, and with the pre-set spray painting speed. Spray painting is started from the upper end of the surface. The communication links to the computer facilitates the programming of the joint controllers by providing access to off-line programming, and access to a high level programming language. Communication software is developed to enable the computer to manoeuvre the robot, and to obtain status information from the joint controllers. Proximity sensors inform the computer with the home position. They also sense the end of the trajectory and inform the computer.

4..Inverse Kinematic Algorithm

Inverse kinematics is concerned with transforming the desired motion trajectory of the end effector in the wointo corresponding motion of the robot joints. This means that at each node, the values of the six joints anglesθ(θ_1 to θ_6 are calculated using the proposed geometrical approach. For a six DOF manipulator, it is difficult to obtain a straightforward geometrical solution for the inverse kinematic problem. This is due to the necessity of relating the desired orientation of the end- effector to the corresponding axial positions. However for the spray painting robot designed in this paper with geometrical simplifications, i.e.the three axes of the wrist intersect in one point, and three parallel revolute axes for the arm joints, a geometrical approach for inverse kinematic solution is possible.

(i)Geometrical Approach

Solution with proposed geometrical approach proceeds as follows:

Choosing the end effector coordinate frame such that the axis of motion is co-directional with the axis of wrist roll, and utilizing the Denavit-Hartenberg transformations [4], the transformation matrix describing the position and orientation of the nth joint to the base coordinate frame is given by:

$$T= \begin{matrix} N_x & O_x & A_x & P_x \\ N_y & O_y & A_y & P_y \\ N_z & O_z & A_z & P_z \\ 0 & 0 & 0 & 1 \end{matrix}$$

Where N is the normal vector, O is the sliding vector, and A is the approach vector of the end effector, &P is the position vector.

Fixing the position of the surface coordinates frame with respect to the wrist frame at a distance of ten cm. from it, the transformation matrix describing the position and orientation of the surface with respect to the end effector (^wT_s), and the transformation matrix describing the position and orientation of the surface with respect to the base (^sT_b) , are calculated. Hence the components of the transformation T, written above, are calculated using the relation:

$$T=[^wT_s].[^sT_b]$$

At this stage, the pertinent solution for the joint angles corresponding to each node on the surface to be painted is calculated by manipulating equations (1) to (10), giving the following expressions for the joint angles, in the order of the manipulation:

$\theta_1=\tan^{-1}[(p_y-d_6.a_y) / (p_x-d_6.a_x)]$

$\theta_5= \tan^{-1}[d_6.(1-(a_y.C_1-a_x.S_1)^2)^{0.5}/(p_y.C_1-p_x.S_1)]$

$\theta_2 + \theta_3 + \theta_4= \theta_{234}=\tan^{-1} [-a_z /(a_x.C_1 + a_y.S_1)]$

for $\theta_5 > 0$

$\theta_{234}= \theta_{234}+\pi$ for $\theta_5 < 0$

$\theta_6 = \tan^{-1}[(O_x .S_1 - O_y .C_1)/ (N_y.C_1 - N_x .S_1)]$

for $\theta_5 > 0$

$\theta_2 =-\tan^{-1}\{[1 - (w/q)^2]^{0.5}/(w/q)\} + \tan^{-1}(u/t)$

$\theta_3 = \tan^{-1}[(u - a_2.S_2)/(t - a_2.C_2)] - \theta_2$

$\theta_4 = \theta_{234} - \theta_2 - \theta_3$

where,

$t=a_2.C_2 + a_3. C_{23} = C_1.P_x + S_1.P_y + d_6.S_5.C_{234} - a_4.C_{234}$

$u = a_2.S_2 + +a_3.S_{23} = -P_z + d_1 - a_4.S_{234} +d_6.S_5.S_{234}$

$w = t.C_2 + u.S_2$

$q = (t^2 + u^2)^{0.5}$

Where, C stands for the cosine of the joint angle 'θ', and S stands for the sine of the joint angle'θ', and for brevity the following compact notations are used:

$C\theta_i=C_i$, $S\theta_i=S_i$,$C(\theta_i +\theta_j)=C_{ij}$,$S(\theta_i+\theta_j)=S_{ij}$, $C(\theta_i+\theta_j+\theta_k)=C_{ijk}$, and $S(\theta_i+\theta_j+\theta_k)=S_{ijk}$ and, a_2, a_3, a_4, d_1, d_6 are the dimensions shown on Fig.(1).

(ii)Singularities

Singularities represent configurations at which the mobility of the structure is reduced, and it is not possible to impose an arbitrary motion to the end effector. Singularity computation is split into two separate problems, arm and wrist singularities, and the values of parameters at which these singularities occur are calculated, and found to be:

a. arm singularities resulting from the motion of the first three links, occurs if $\theta_3=0$ or π (elbow is outstretched or retracted), or if $P_x=Py=0$ (shoulder singularity).
b. wrist singularities ,and is found to occur at $\theta_5=0$ or π

These values are accounted for in the developed inverse kinematic software.

Workspace Limits

The developed inverse kinematic software included computation of the extreme reaches of the designed robot. These limits depend on the dimensions of the robot arms as well as on the range of allowable rotation for each joint. For the 6 DOF robot geometry shown in Figs.(1)&(2), the upper and lower bounds on the three axes X,Y, and Z are geometrically calculated and found to be:

$$0 \le X \le a_2 + a_3 + \beta_1$$

$$(R_{min}{}^2 - X^2) \le Y \le [(a_2 + a_3 + \beta_1)^2 - X^2]^2$$

$$Z_{max} \le \beta_2 + \{(a_2 + a_3)^2 - [(X^2 +Y^2)^2 - \beta_1]^2\}^{0.5}$$

$$Z_{min} \le \beta_2 - \{(a_2 + a_3)^2 - [(X^2 + Y^2)^2 - \beta_1]^2\}^{0.5}$$

Where,

$\beta_1 =a_4 \cos \Psi_1 +d_5 \sin\Psi_1$

$\beta_2 =a_4 \sin \Psi_1 - d_5\cos \Psi_1 + d_5$

$R_{min}=2 +3*\cos \Psi_1 + 12*\sin\Psi_1$

$R_{max}= a_2 + a_3+ \beta_1$

$\Psi_1= \theta_2 + \theta_3 + \theta_4 - \pi$

5.Simulation Examples

The developed inverse kinematic software is applied to find the position and speed trajectories for the six joints angles when painting a rectangular plane surface and a hemisphere.

(i) Spray Painting of a Rectangular Surface.

The surface of dimensions 60cm* 40 cm is placed at a distance of 10 cm from the spraying nozzle edge, and the CCD cameras adjusted to feed the computer with the surface dimensions. The two, two-dimensional photos taken by the cameras for the surface to be sprayed, from two different positions, are transformed into the three dimensions of the surface via a developed software loaded in the main computer. These three-dimensional data are applied to the developed inverse kinematic program to determine the spraying paths. These paths consist of parallel straight line segments, and each segment is divided into nodes that define the joint pauses, as explained in section 3.Setting appropriate initial values to the joints angles, painting is started from the upper segment of the surface, with a trapezoidal speed profile. The speed starts from zero to 0.6m/sec. The aim of such speed profile is to allow the homogenity of the spraying process at the starting and the finishing intervals of each straight line segment, as well as during the motion of the spraying nozzle from an upper segment to a lower one. As the spray-painting process is finished the computer receives signal to close the spraying nozzle. The position and velocity trajectories of some of the six robot joints until the surface is fully painted are plotted in figures (3) to (6). The trapezoidal speed trajectory proposed, is obvious in the trajectories at start and end of each line segment.

(ii) Spray Painting of a Hemisphere

The hemisphere is divided theoretically into circular planes. Each plane is subdivided into small segments, to define the nodes (joint pauses) at which the joint angles are to be calculated. The same procedures for spray painting of the rectangular surface is followed. The difference between the two cases is in the orientation of the surface coordinates, where the center of the hemisphere is considered as the origin of the surface coordinates, to simplify defining the position and orientation of the spraying gun at each node. The position and velocity trajectories for some of the six robot angles are plotted in figures (7) to (10).

6..Conclusion

An economic automatic system for spray painting of a general three dimensional surface is described. The spray gun is mounted on the wrist of a six degree of freedom (6 DOF) industrial robot. The system functions by the method of camera space manipulation, using two CCD cameras to scan the surface dimensions off-line, and store them in a supervisory computer in the form of nodes. An inverse kinematic program is composed and stored in the computer to calculate the angles of the six joints corresponding to each node on the surface, to acquire the correct position and orientation of the spray gun. The values of the joint angles are fed to the micro-controllers controlling the joint motors every time interval ,depending on the number of nodes and the required spray painting rate. The computer receives sensory data from the micro –controllers as job is accomplished. The position and velocity trajectories of two surfaces with different geometries (rectangular and hemispherical) are calculated using the proposed algorithm, and plotted for each of the six joints. The advantages of the proposed spray painting technique can be summarized as:

1.Cost reduction by decreasing the number of sensors.
2.Cameras do not move during object scanning, which reduces the complexity of the controls required ,and hence decreases expenses.
3.Different shapes could be painted without consuming time in trajectory planning for each special geometry.
4.Precise spray painting system is attained due to considering singularities during inverse kinematic solution

These lead to a simple economic and robust spray painting system.

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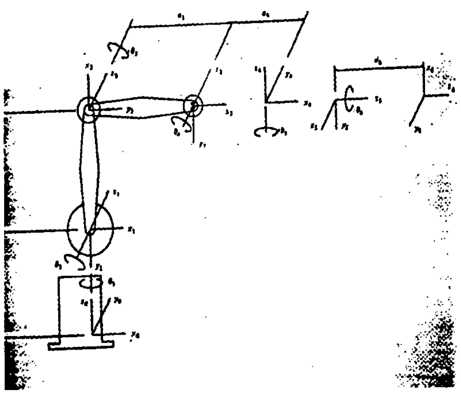

Fig.(1) Robot Arm

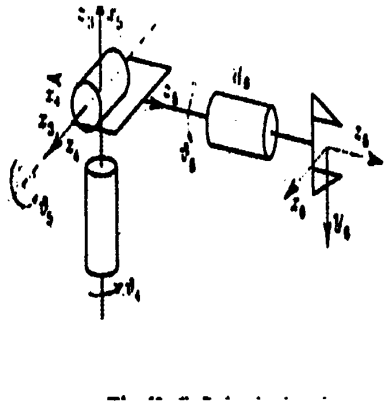

Fig.(2) Robot Spherical Wrist

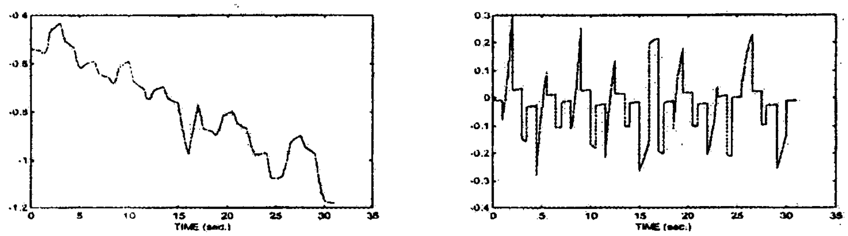

Fig.(3)Position and Speed Trajectories of Joint 2

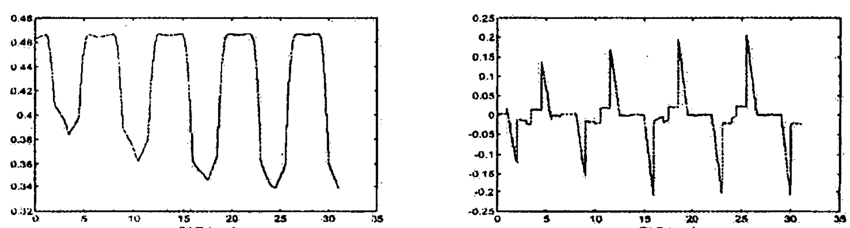

Fig.(4) Position and Speed Trajectories of Joint 3

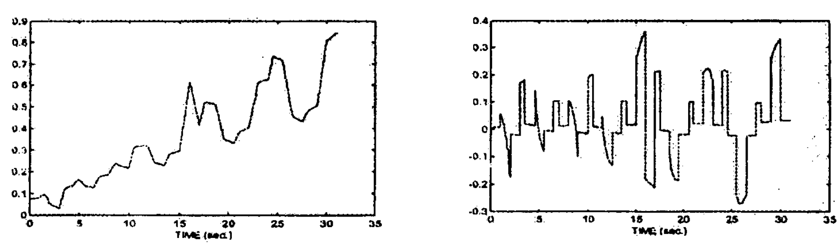

Fig.(5) Position and Speed Trajectories of Joint 4

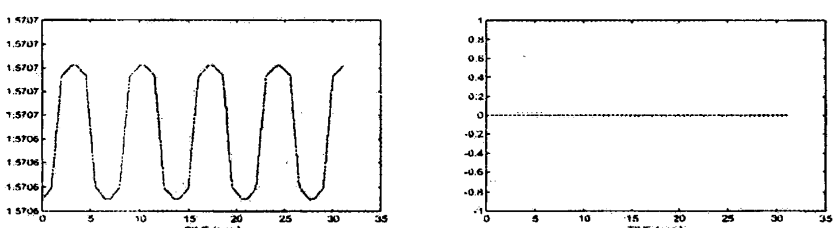

Fig.(6) Position and Speed Trajectory of Joint 5

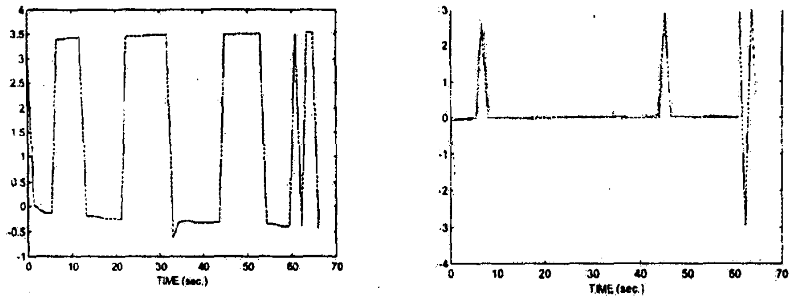

Fig.(7) Position and Speed Trajectories of Joint 3 for the Hemisphere

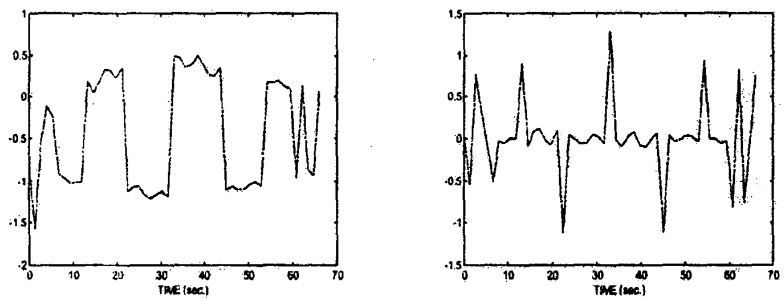

Fig.(8) Position and Speed Trajectories of Joint 4 of the Hemisphere

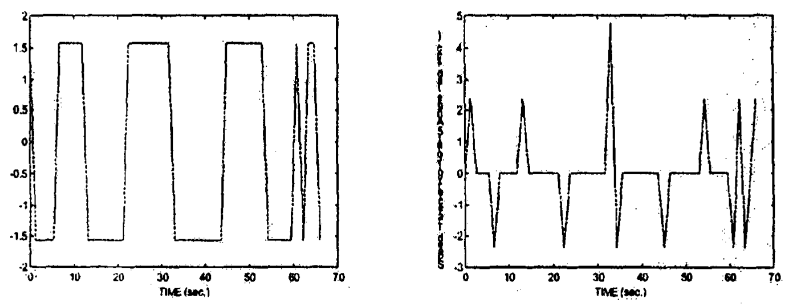

Fig.(9) Position and Speed Trajectories of Joint 5 for the Hemisphere

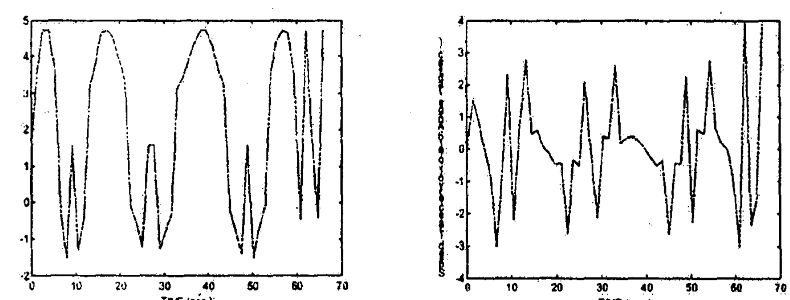

Fig.(10) Position and Speed Trajectories of Joint 6 for the Hemisphere