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Six DOF Spray Painting Robot Analysis

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ABSTRACT: Today, different kinds of robots are being used in many fields. Especially in industries, robots are essential. One application in the industries is spray painting task which is no more suitable for human workers because it have large effect on health. Also the spray painting is a challenging task and need significant skill. Thus, spray painting robot are using wider and wider. This paper represents the analysis of a spray painting robot. Calculations and analysis are made to get the position and orientation of end effector. Also the spray painting patch and angles of each joint are calculated in this analysis. Position and orientation of end effector are analysed by forward kinematic. The angles of each joint are find out by inverse kinematic. Denavit- Hartenberg (D-H) methods are used in forward and inverse kinematic. Spray painting patch is generated by finding the equation of the surface of regular shape work-piece. Measurement and observation of robot are made on SolidWorks software. In this analysis, the calculation is quite complex and containing many variables even in an element of a matrix. Such kind of long equations are simplified by using MATLAB software.

KEYWORDS: Spray Painting Robot, DOF, Kinematics, System Security.

I. INTRODUCTION

Spray painting is a painting technique where a device sprays a coating (paint, ink, varnish etc.) through the air onto a surface. The most common types employ compressed gas (usually air) to atomize and direct the paint particles. Spray guns evolved from airbrushes, and the two are usually distinguished by their size and the size of the spray pattern they produce. Airbrushes are hand-held and used instead of a brush for detailed work such as photo retouching, painting nails or fine art. Air gun spraying uses equipment that is generally larger. It is typically used for covering large surfaces with an even coating of liquid. Spray guns can be either automated or hand-held and have interchangeable heads to allow for different spray patterns. Industrial painting robots can provide exceptional part accessibility. Not only robotic arms are slim and far-reaching, but robots can be installed in a number of different locations (wall, shelf, rail) allowing for even greater flexibility. Anti-collision software makes it possible for multiple robots to work in close proximity to one another. With more robots working together, throughput and cycle times improve.

II. BACKGROUND

The history of robots has its roots as far back as ancient myths and legends. Modern concepts were begun to be developed when the industrial revolution allowed the use of more complex mechanics and the subsequent introduction of electricity made it possible to power machines with small compact motors. After the 1920 the modern formulation of a humanoid machine was developed to the stage where it was possible to envisage human sized robots with the capacity for near human thoughts and movements, first envisaged millennia before. The first uses of modern robots were in factories as industrial robots – simple fixed machines capable of manufacturing tasks which allowed production without the need for human assistance. Digitally controlled industrial robots and robots making use of artificial intelligence have been built since the 1960. An industrial robot is defined as an automatically controlled, reprogrammable, multipurpose manipulator programmable in three or more axes. The field of robotics may be more practically defined as the study, design and use of robot systems for manufacturing. Typical applications of robots include welding, painting, assembly, pick and place (such as packaging, palletizing and SMT), product inspection, and testing; all accomplished with high endurance, speed, and precision. The most commonly used robot configurations are articulated robots, SCARA robots, Delta robots and Cartesian coordinate robots, (aka gantry robots or x-y-z robots). In the context of general robotics, most types of robots would fall into the category of robotic arms. Industrial paint robots

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have been used for decades in automotive paint applications from the first hydraulic versions - which are still in use today but are of inferior quality and safety - to the latest electronic offerings. The newest robots are accurate and deliver results with uniform film builds and exact thicknesses.

Figure 1. Painting Robot

Originally, industrial paint robots were large and expensive, but today the price of the robots have come down to the point that general industry can now afford to have the same level of automation that only the big automotive manufacturers could once afford. The selection of today's paint robot is much greater varying in size and payload to allow many configurations for painting items of all sizes. The prices vary as well as the new robot market becomes more competitive and the used market continues to expand.

Painting robots are generally equipped with five or six axis, three for the base motions and up to three for applicator orientation. These robots can be used in any explosion hazard class 1 division 1 environment. Automatic painting is also used to describe painting using a machine or robot. Industrial robots have been used for decades in automotive applications, including painting, from the first hydraulic versions, which are still in use today but cannot match the quality or safety of the electric robots, to the latest electric offerings from the robot original equipment manufacturers. The newest robots are more accurate and deliver better results with uniform film builds and precise thicknesses.

Originally, industrial paint robots were big and expensive, but today the price of the robots, new and used, have come down to the point that general industry can now afford to have the same level of automation that only the big automotive manufacturers could only once afford. The selection of today's paint robots is much greater; they vary in size and payload to allow many configurations for painting big items like Boeing 747s and small items like door handles. The prices vary as well, as the new robot market becomes more competitive and the used robot market continues to expand.

Degree of Freedom

The degree of freedom of a mechanism is the number of independent parameters or inputs needed to specify the configuration of the mechanism completely. Except for some special cases, it is possible to drive a general expression for the degrees of freedom of a mechanism in terms of the number of links, number of joints, and types of joints incorporated in the mechanism.

The degree-of-freedom value of a mechanism is equal to the degrees of freedom associated with all the moving links minus the number of constraints imposed by the joints. Hence, if the links minus the number of constraints imposed by the joints. Hence, if the links are all free of constraints, the degrees of freedom of an n-link mechanism, with one of its links fixed to the ground, would be equal to λ (n-1). However, the total number of constraints imposed by the joints is equal to

$$\sum_{i=1}^{j} Ci$$

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Hence the degree-of-freedom value of a mechanism is generally given by:

$$F = \lambda\,(n-1) - \sum_{i=1}^{j} Ci$$

Orientation and Dimension:

The orientation of a rigid body with respect to the fixed frame can be described in several different ways. The direction of cosine representation followed by the screw axis representation and then the Euler angle representation. To describe the orientation of a rigid body, the motion of a moving frame B with respect to a fixed frame A with one point fixed. This is known as a rotation or a spherical motion. Without losing generality that the origin of the moving frame is fixed to that of the fixed frame. In three dimensions, the six DOFs of a rigid body are sometimes described using these nautical names:

a. Moving up and down(heaving)
b. Moving left and right (swaying)
c. Moving forward and backward(surging)
d. Tilting forward and backward (pitching)
e. Turning left and right(yawing)
f. Tilting side to side (rolling)

Linking Parameter:

In general, an n-DOF serial manipulator consists of a base link and n moving links connected in series by n joints without forming a closed loop. The relative motion associated with each joint can be controlled by an actuator such that the end effector can be positioned anywhere within its workspace. To describe the geometry of the links, starting from the base link sequentially from 0 to n and the joints from 1 to n. Thus, except for the base link and the end-effector link has two joints. Link 1 is connected to the base link by joint 1; link 2 is connected to link 1 by joint 2, and so on. Link i has joint I at its proximal end and joint i+1 at the distal end.

Following Denavit and Hartenberg's convention (1955), a Cartesian coordinate system is attached to each link of a manipulator. Except for the base and end-effector link, coordinate system i is attached to link i according to the following rules:

- The z_i axis is aligned with the $(i+1)^{th}$ joint axis. The positive direction of rotation or translation can be chosen arbitrarily.
- The x_i axis is defined along the common normal between the i^{th} and $(i+1)^{th}$ joint axes and point from the i^{th} to the $(i+1)^{th}$ joint axis. If the two joint axes are parallel, the x_i axis can be chosen anywhere perpendicular to the two joint axes. In case of two intersecting joint axes, the x_i axis can be defined either in the direction of the vector cross product z_i-1 x z_i or in the opposite direction, and the origin is at the point of intersection.
- The y_i axis is determined by the right hand rule.

Denavit-Hartenberg Homogeneous Transformation Matrices:

Having established a coordinate system to each link of a manipulator, a 4X4 transformation matrix relating two successive coordinate systems can be established. Observation of the i^{th} coordinate system can be thought of as being displaced from the $(i-1)^{th}$ coordinate system by the following successive rotations and translations.

The resulting transformation matrix ${}^{i-1}A_i$, is given by:

$${}^{i-1}A_i = T(z,d)T(z,\Theta)T(x,a)T(x,\alpha)$$

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3.1 Forward Kinematics

The forward kinematics problem is concerned with the relationship between the individual joints of the robot manipulator and the position and orientation of the tool or end- effectors. Stated more formally, the forward kinematics problem is to determine the position and orientation of the end-effector, given the values for the joint variables of the robot. The joint variables are the angles between the links in the case of revolute or rotational joints, and the link extension in the case of prismatic or sliding joints. The forward kinematics problem is to be contrasted with the inverse kinematics problem, which will be shown in the next topic, and which is concerned with determining values for the joint variables that achieve a desired position and orientation for the end-effectors of the robot.

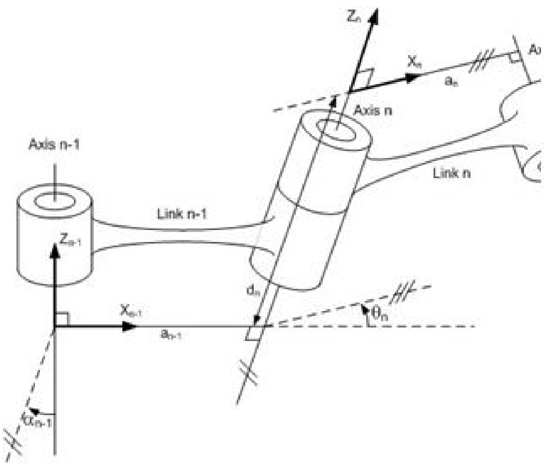

Figure 2. Revolute joints for manipulator kinematics

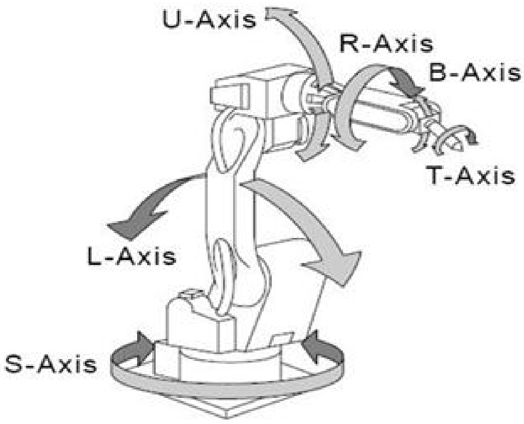

Figure 3. Industrial 6 DOFs articulated robotics arm

In robotic control, it is of great importance to know the position of the robot tip, or end effecter, in world coordinates. When modelling a robotic system, researchers commonly use DH notation to specify a robot's geometry and the industrial 6 degrees of freedom (DOFs) articulated robotics arm is a common benchmark robotic system that has full mobility (six-axis) and utilizes both prismatic and revolute joints. A simplistic model of a robot as a collection of links connected by joints is very often insufficient. Engineers use the Denavit-Hartenberg convention (D-H) to help them describe the positions of links and joints unambiguously.

Denavit-Hartenberg Parameters is a commonly used convention for selecting frames of reference in robotics applications is the Denavit and Hartenberg (D-H) convention which was introduced by Jaques Denavit and Richard S. Hartenberg. In this convention, each homogeneous transformation is represented as a product of four basic transformations. The common normal between two lines was the main geometric concept that allowed Denavit and Hartenberg to find a minimal representation. The transformation is described by the following four parameters known as D-H Parameters.

$\mathbf{a_n}$ is the length of link from axis Z_{n-1} to Z_n follow X_n
$\boldsymbol{\alpha_n}$ is the twist angle from axis Z_{n-1} to Z_n around X_n
$\mathbf{d_n}$ is the offset distance from axis X_{n-1} to X_n around Z_{n-1}
$\boldsymbol{\theta_n}$ is the angle from axis X_{n-1} to X_n around Z_{n-1}

Since only four parameters are used, the frames that can be represented this way has to satisfy two more constraints

1. the X_n axis is perpendicular to the Z_{n-1} axis
2. the X_n axis intersects Z_{n-1} axis

Every link/joint pair can be described as a coordinate transformation from the previous coordinate system to the next coordinate system

$$ {}^{n-1}{}_{n}T = Rot_{Z_{n-1}}(\theta) \times Trans_{Z_{n-1}}(d_n) \times Trans_{X_n}(a_n) \times Rot_{X_n}(a_n) $$

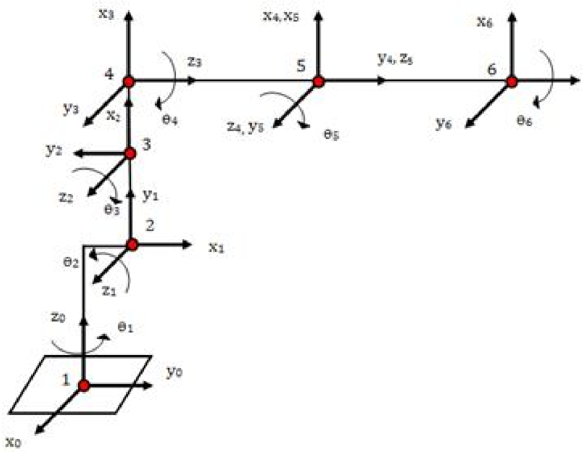

Figure4. Link coordinates diagram of the robot arm

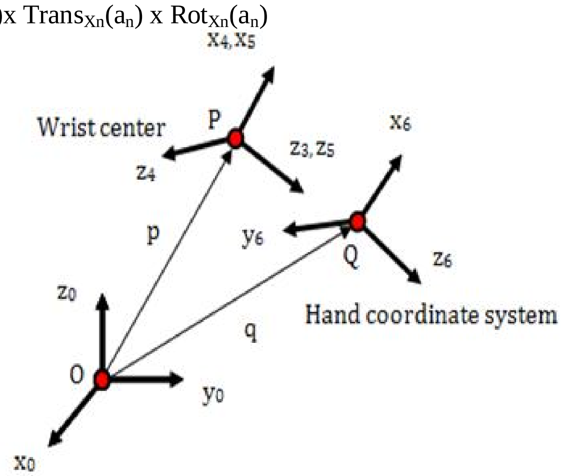

Figure5. Hand coordinate system and wrist centre position

Inverse Kinematics

1. Forward Kinematics is a mapping from joint space Q to Cartesian space W:

$$F(Q) = W$$

This mapping is one to one, there is a unique cartesian configuration for the robot for a given set of joint variables. Inverse Kinematics is a method to find the inverse mapping from W to Q:

$$Q = F^{-1}(W)$$

2. The inverse kinematics problem has a wide range of applications in robotics. Most of our high level problem solving about the physical world is posed in Cartesian space. While we can reason bout the physical world in Cartesian terms, the robot is actuated in joint space that is what we ultimately can control. Once we solve a problem for its Cartesian space constraints, we need to map these constraints into the robot's joint space using inverse kinematics. For example, if we specify a straight line trajectory for a robot arm, we need to break that trajectory into a set of joint space values over time to get the robot to follow the line.
3. The inverse kinematics mapping is typically one to many. There are usually multiple sets of joint variables that will yield a particular Cartesian configuration. When solving the inverse problem, we often have to choose one solution from a number of valid solutions. There are also degenerate cases with an infinite number of solutions (called singularities).
4. Some solutions of the inverse mapping may not be physically realizable. This is due to manipulators having physical joint limits that prevent the mechanism from achieving certain joint configurations that may be solutions to the inverse kinematics problem (e.g. a joint may not have a full 360 degree motion).
5. There may not be a closed form solution to the inverse problem at all for some manipulators.
6. Numerical methods can be used to find a solution to the inverse problem if a closed form solution does not exist.
7. A redundant robot is one that has extra DOF's (more than the space the robot works in requires).
8. To solve inverse kinematics, we use a variety of methods: geometric, trigonometric and algebraic. There are

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certain forms that you can recognize and then use the appropriate method to solve for a joint variable.

9. Once you solve for a joint variable, you can think of the manipulator as a reduced DOF mechanism with one less joint. Now solve this manipulator's inverse problem and keep doing this until all joints are solved for.
To illustrate the use of the inverse kinematic heuristic in finding the general solution for a manipulator, we will find the arm solution for the industrial 6 DOFs articulated robotics arm manipulator

Wrist Center Position:
Note that the last three joint axes intersect at the wrist center point P. Hence rotation of the last three joint do not affect the position of P. The end-effect coordinate system (x6, y6, z6), the wrist center P, and the vector relation between them. The wrist center position with respect to and expressed in the end-effector coordinate system is

$$P6 = QP = [0,0,d_6, 1]^T$$

IV. KINEMATIC ANALYSIS

4.1. Kinematic Analysis
Kinematic analysis is the explanation, which shows the orientation and robot's movement in term of matrix. In fact, factors of transformation of the robot consist of position and angle in each joint. For this chapter, all of the factors are analyzed and connected with important theories to optimize equations easily. Many theories are used, such as D-H Homogenous Transformation Matrices, Degree of freedom, Roll Pitch and Raw Metric and etc.

4.2. DOF of the Robot
The first concern in a study of the kinematics of mechanism is the number of degrees of freedom. Therefore, the DOFs are defined as the following equation

$$F = \lambda\ (n - j - 1) + \sum_i f$$

Where

F = Degree of freedom
λ = Degree of freedom of the space = 6
n = number of links = 7
j = number of joints = 6
f = degrees of relative motions = 6

Thus, degrees of freedom are

$$F = 6(7 - 6 - 1) + 6 = 6$$

Dimension of the Robot

In general, all of the distances in each position are defined as the specification of the robot otherwise there is some value which needed to measure consists of:

The distance between joint 2 and 3
This value is used to calculate the angle 3 (teta3) (in inverse kinematic topic)

$$D24 = \sqrt{(170)2}$$

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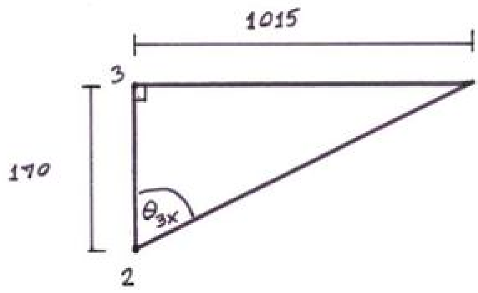

Figure6. The distance between joint 2,3 and 4

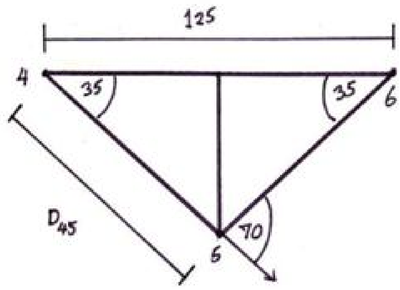

Figure7. The distance between joint 4 and 5

This value is used to determine the angle 5 (teta5) because in reality, a painting arm is able to change or install many type of spray injector.

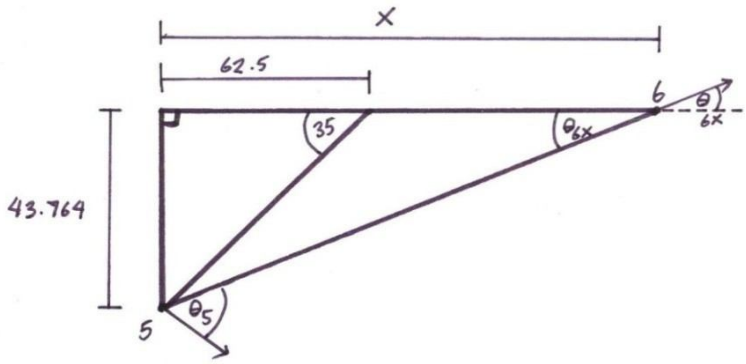

Figure8. The distance between joint 5 and 6

Forward Kinematic

For the coordinate system, the link parameters are given in table 3. Substituting all of the parameters into the transformation matrix, the transformation matrix of each joint will be written as follow.

Table 1: DH Transformation Matrixes

Joint	(alpha)∝	(a)ai	(d)di	(teta)θ
1	90	0	440	θ1
2	0	1000	0	θ2
3	90	170	0	θ3
4	-35	0	1015	θ4
5	70	0	76.3	θ5
6	-35(X)	0	76.3(X)	θ6

In fact, the end effector location can be computed by using transformation matrix and trigonometry. Therefore,

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to recheck the transformation matrix correctly, the value of both methods would be the same.
Example 1: *If the angle of the actuators are given below*

Table 2: Transformation Matrixes of Spray Painting Robot

Joint	(alpha)∝	(a)ai	(d)di	(teta)θ
1	90	0	440	0
2	0	1000	0	30
3	90	170	0	60
4	-35	0	1015	90
5	70	0	76.3	0
6	-35(X)	0	76.3(X)	0

The result is $q = 2006i + 0j + 1110k$
Calculation by hand,

$$q_{06}\ x = 1000\cos 30 + 170\cos 60+30 + 1015 + 76.3\cos 35 + 76.3\cos 35$$

$$= 2006$$

$$q_{06}\ y = 0$$

$$q_{06}\ z = 440 + 1000\sin 30 + 170\sin 60+30 = 1110$$

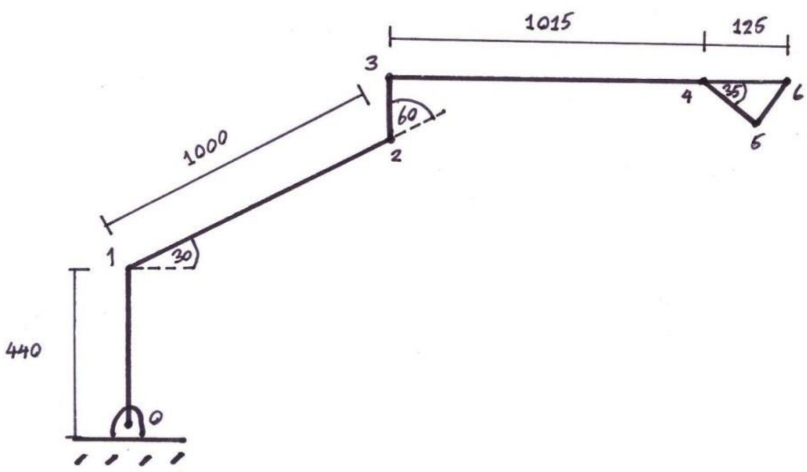

Figure9. Robot Skeleton

Inverse Kinematic

To analyze the angle of the motor, there are two methods consisting of direct kinematic and inverse kinematic. Direct kinematic is used to transfer the end effector position when the angle of the motors are obtained. On the other hand, the movements of the actuators are needed to know after the object locations are also known. Therefore, the inverse kinematic are used to determine the angle of the actuators

First of all, there are 6 transformation matrixes and 1-3 transformation matrixes are important to move the end effector of the robot to locate the nearest object location. Moreover the 4-6 transformation matrixes duties are to

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control both of the direction and position of the robot to be perpendicular to the surface of the object.

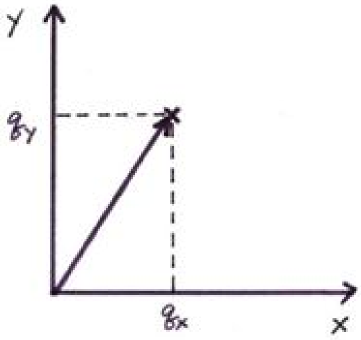

Figure10. Angle 1(Θ_1)

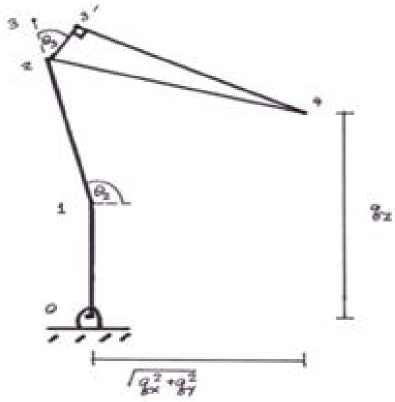

Figure13. Angle 2 and 3(Θ_1 and Θ_2)

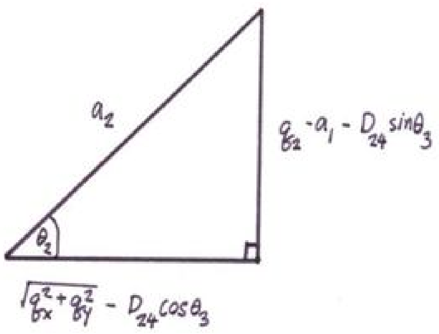

Figure11. Trigonometry of link 2 and 3

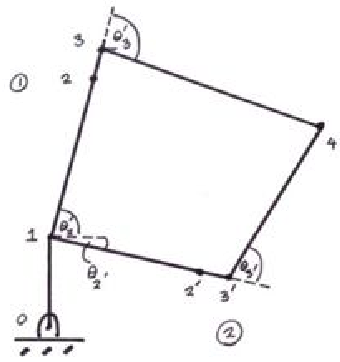

Figure14. Methods of movement of link 2 and 3

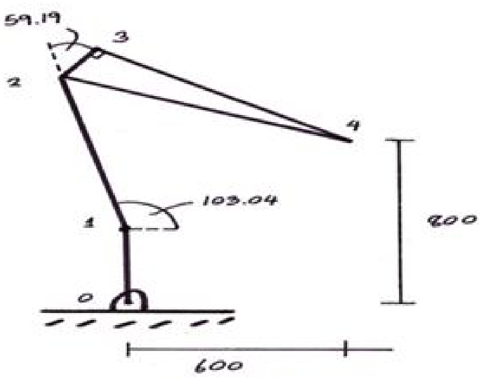

Figure12. Θ_1, Θ_2 and Θ_3

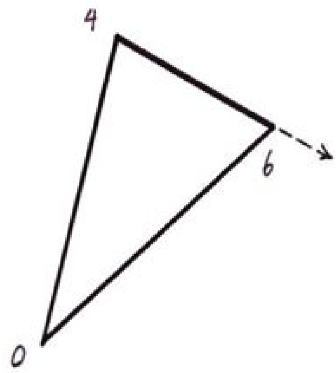

Figure15. $P_{06} = P_{04}+P_{46}$

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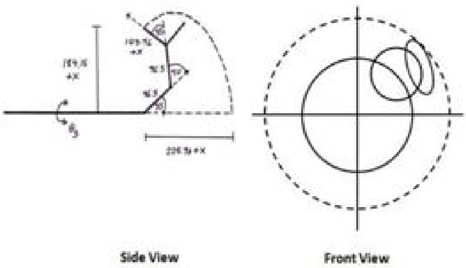

Figure16. Robot movement properties

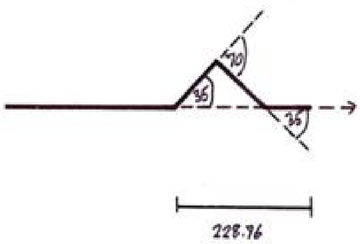

Figure17. End effector longest distance

2. When the values for the joint variables of the robot are given, we can know the transform matrix of every joint, position and orientation of the end-effector can be defined by forward kinematic method.

3. We can also specify a trajectory for a robot arm, we need to break that trajectory into a set of joint space values over time to get the rotational equation of every joint, which is inverse kinematic. However, in this case study we have only solved inverse kinematic problem of given points on the work piece and got the rotational value of each joint instead of solving the rotational equation, because the calculation process of motion analysis of the spray painting robot is too complicated.
4. When solve for a joint variable, we can think of the manipulator as a reduced DOF mechanism with one less joint, which will make the calculation easier. Solve this manipulator's inverse problem and keep doing this until all joints are solved for.
5. We conclude that corresponding to each solution set of the first three joint angles, there are two possible wrist configurations. However, due to mechanical limits, fewer than eight manipulator postures are physically realizable.
6. The spray painting robot in our study is designed for automotive industry using. We assume the object as a sphere, and generate the sphere surface in MATLAB software. To reduce the calculation, we do linear approximation by using 10×10 planes to approach the sphere.
7. In order to make the spray painting robot reach every point of the sphere, appropriate work piece offset have to be designed. By taking the limitation of movement of each joint, we According to the position analysis, the last three joint axes intersect at the wrist center point.

V. CONCLUSION

Thus it allows each node with message to decide whether to copy the message to a path node by optimizing its transmission effort in order to provide a sufficient level of message delay. Using a channel selection scheme provides spectrum utilization while it minimizes the interference level to primary system. Using trustworthy algorithm, it improves the trustworthiness of the Spectrum sensing in CR-Networks. It enables network nodes to adaptively regulate their communication strategies according to dynamically changing network environment.

VI. ACKNOWLEDGEMENT

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