USING GENETIC ALGORITHM FOR SINGULARITY AVOIDANCE IN POSITIONING TASKS OF A ROBOTIC ARM

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Abstract: In this paper, the singularity problem is addressed. We studied the singularity of a real arm robot analytically and numerically. Then, using genetic algorithm techniques we present a new method to decrease the effects of the singularity. This allows the robot to avoid the failure of the positioning task when the robot is to pass near or pass through a singular configuration. In the proposed technique, to determine the alternative robot configurations parameters, a global objective function is designed to minimize both the error between the end-effector positions at the singular and the alternative configurations and the error between the robot joints values at the singular and the alternative configurations. Finally, an avoidance task function is proposed. The proposed solutions are implemented and the results obtained from genetic algorithm are validated when positioning tasks are performed the real arm robot. Also, the results of the proposed avoidance technique show that it allows the robot to avoid the singularity effects when the arm robot is to perform positioning tasks.

Keywords: Robot forward kinematics, Robot singularities, 5 Degree of freedom (DOF) robot arm singularity, Avoiding singularity, Genetic Algorithm.

Introduction

Since the invention of robots in mid 19th century, a lot of researches have been dedicated to study the robot kinematics, inverse kinematics, forces, joints dynamics and joints torques. Singularity analysis has been identified as a very important subject in robotic due to its effects on the robot because it causes robot joint velocity enlarged and tends to infinity. This can lead to instability in robot motion, reduce instantaneous mobility of the robot, can alter the path planned, may impede control algorithms, forces and torques, and damage the robot internal mechanisms causing a catastrophic situations, [De Xu, 2005; Jasour, 2009].

At singular configuration the determinant of the Jacobian matrix becomes zero causing the infinite joint velocities. Jacobian matrix is the coefficient matrix of the set of equations which relate the velocity of the end effector with the robot joints velocities. The Jacobian matrix is thus a critical element through robotics applications, especially in finding the singular points in the work space of a serial robot. Singularity issue is defined and studied by [Gosselin, 1990], where different kinds of singular configurations are defined for various closed loops robot manipulators in [Zlatanov,1994a; Zlatanov, 1994b; Hayes, 2002]. The formulation of Jacobian presented in current work is built upon the material found in [Sciavicco, 2000; Siciliano, 2008; Craig, 2005].

Many efforts were done to find the singularity of a specific arm robot to derive the conditions which identify the properties of the singularity. Some researchers used the screw theory or coordinate transformations [Lai, 1986; Wang, 1987; Hunt, 1991; Sefrioui, 1993], other researchers used a geometrical approach which will also be used in current work, [Gosselin, 1990; Merlet, 1988; Merlet, 1989]. A six degrees of freedom robot arm manipulator from has been studied in [Vaezi, 2011] with full scope of the robot arm singularities to decompose the robot arm singularities the wrist singularities. The work presented in [Hayes, 2002] studies an analytical description and classification of the complete set of singular configurations of the KUKA KR-15/2 six-axis serial robot in particular and all wrist partitioned 6R robots in general. The analysis shows that all general singular positions are either shoulder, elbow, or wrist singularities, or any combination thereof, no others exist.

The paper is organized as following: in section two, some related works are presented then robot structure and Jacobian matrix are discussed. The problem definition of the CRS robot singularities is discussed and studied analytically and numerically in section three. The proposed solutions using genetic optimization and avoidance function are given in section four. The implementations of the proposed methods and the experimental results are presented in section six. Finally, section seven discusses the conclusions.

Related Works

Genetic algorithm (GA) is a powerful method to optimize a wide range of problems, it has been used to optimize problems in many fields such as military, industrial, biological, financial, economical, engineering, medical, and robotic fields. In the robotic field many researchers have used Genetic algorithm to optimize and find the best path and trajectories for the robot arm to move between different points, [Latombe, 1991; Chan, 1993; Bianco, 2002; Devendra, 2002; Pires, 2000].

Genetic algorithm is also used to maximize the reachable area in the work space by end effectors of the robot [Chaitanyaa, 2016; Stan, 2009; Khoshnoodi, 2017]. In [Chaitanyaa, 2016] optimization is used to maximize the work space area reached by the end effector of a revolute robotic arm. The singularities influences of the design variables variation is considered when the mathematical model used for the optimization is designed. Link lengths and Joint angle between link1 and link 2 are modeled as design variables. Nonlinear optimization model based on Genetic Algorithm employed to obtain a global optimum value of the objective function is compared with the using of semi-infinite programming technique, [Chaitanyaa, 2016]. The results showed that Genetic algorithm gives a maximum objective function value which is considerably high compared with the value obtained using the semi-infinite programming method.

Genetic algorithm is also used in [Stan, 2009] in workspace maximization problem of a 2-DOF parallel robot and sowed that using GA in optimization problems improves the quality of the outcome from the optimization. Genetic Algorithm is used in [Khoshnoodi, 2017] to determine the optimum manipulator dimensions when the singularity and kinematic properties are used to define the objective function. Their work show that using genetic algorithm in the optimization allows to achieve ideal design of parallel manipulator geometry with minimum singularity and good workspace. In this research work the genetic algorithm technique is used to find alternative configurations to those singular configuration of a five degrees of freedom arm robot. The structure of the CRS Robot Arm is presented and the robot Jacobian matrix are now discussed and explained.

2.1 Structure of the CRS Robot Arm

The CRS robot arm consists of five rotating joints each joint has its axis of rotation as in Figure 1.

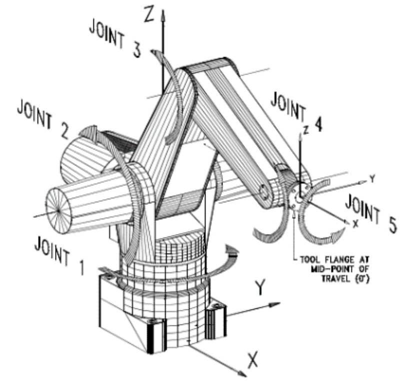

Figure 1: CRS Robot Arm

The complete system comes with a controller and a teach pendant. Robot arm is either controlled through an open or closed architecture mode. In the open architecture mode, the robot arm is controlled by Matlab, while in the closed architecture it is controlled through the teach pendant. The DH parameters representing the robot arm is shown in Table 1.

Table 1: CRS DH parameters

Link	Alpha	Angle offset	Theta	Distance
1	0	0	0	0
2	$\boldsymbol{\pi l2}$	0	$\boldsymbol{\theta_1}$	254
3	0	254	$\boldsymbol{\theta_2}$	0
4	0	254	$\boldsymbol{\theta_3}$	0
5	$\boldsymbol{-\pi l2}$	0	$\boldsymbol{\theta_4}$	0
6	0	0	$\boldsymbol{\theta_5}$	50.8

2.2 CRS Robot Jacobian Matrix:

The Jacobian matrix maps the linear and angular velocities of the end effector to the joint velocities. Singularity of the robot occurs when Jacobian matrix tends to zero. The first step in studying the singular configurations is to obtain the Jacobian matrix. The velocities v of the end effector which consists of the linear and rotational velocities is given by:

$$v = J_{CRS}\dot{Q} \tag{1}$$

where $\dot{Q}$ represents the change in every joints angle with respect to time, and J_{CRS} is the jacobian matrix to be computed. The velocity vector of the end effector is given by $v = [\dot{x}, \dot{y}, \dot{z}, \dot{w}_x, \dot{w}_y, \dot{w}_z]$ and the angular velocity vector of robot joints is given by $\dot{Q} = [\dot{\theta}_1, \dot{\theta}_2, \dot{\theta}_3, \dot{\theta}_4, \dot{\theta}_5]$.

The Jacobian matrix $\boldsymbol{J_{CRS}}$ is of size $m \times n$, where m identifies the number of degrees of freedom for the arm robot and n represents the number of joints within the arm robot. Each row in the Jacobian matrix represents the effect of each joint on the coordinate of the end-effector. The geometrical Jacobian of the robot arm can be shown in equation (2):

$$J_{CRS} = \begin{bmatrix} k_1 & k_2 & \dots & \dots & k_5 \\ 0 & 1 & 1 & 1 & 0 \\ 0 & 0 & 0 & 0 & 1 \end{bmatrix} \tag{2}$$

where $k_i = (z_i^0 \times (o_5^0 - o_{i-1}^0))$ with z_i^0 is the vector representing the axis of rotation of the joint i and o_i^0 is the origin point of frame attached to joint i.

Problem Definition

The main problem to be solved in this work is to reduces and avoid the effect of the joint singularity of the CRS robotic arm. This effects can be recognized in the instability of robot motion when it has to approach, pass through, or reach this singular configurations. A new joint singularity in the work space of the CRS arm robot is discovered. The singularity conditions of the robot are studied in order to find the singular configuration of the robot. Two approaches are used for this study analytical and numerical approaches.

3.1 Analytical Study

Singular configurations are reached when the robot configuration causes $|J_{CRS}| = 0$. Thus, the determent of Jacobian has to be obtained to find the configurations that will cause the Jacobian lose a rank or to be ill-conditioned. The determent F of the Jacobian J_{CRS} can be computed and written as:

$$F = |J_{CRS}| = kf(\theta_1, \theta_2, \theta_3, \theta_4, \theta_5) \tag{3}$$

where k is a constant value. $k = (16387064/5)$. and $f(\theta_1, \theta_2, \theta_3, \theta_4, \theta_5)$ is a nonlinear function of robot joint angles $\theta_1, \theta_2, \theta_3, \theta_4$, and θ_5. When setting $F = 0$ in equation (3), we deduced that the number of configurations satisfying this condition are two. First configuration is reached when $\theta_2 = 135$, and $\theta_4 = -45$. Such configuration is equivalent to the shoulder singularity which is not achievable in real time due to mechanical limitation in joint 2. The second singular configuration is reached when $\theta_3 = 0$ and is equivalent to elbow singularity, it can be achieved by the robot in the real time experiments and this singularity will be studied in this work.

3.2 Numerical Study

In the Numerical study, the whole workspace of the robot arm is analyzed to investigate all the possible robot arm configurations which lead to disturbance in robot operations. A simulation program was developed to study the singularities in the robot workspace by considering two different steps for each joint with step size 0.5 and 0.1. The simulation aims to observe all configurations that produce a determent value of the Jacobian less than 0.001, i. e. tends to zero value. These simulation studies show that the disturbances take place for all configurations having $\theta_3 = 0$ which is corresponding to an elbow singular configuration obtained by the analytical study.

This configuration is then analyzed in more detailed by studying the values of the determent starting at $\theta_3 = 0$, corresponding to elbow singularity, to reach $\theta_3 = 0.1$. The goal of this study is to determine when the singularity effect starts to take place and should be avoided. It is found that at $\theta_3 = 0.0001$ the determent value reaches 34.5, and at the fourth step when $\theta_3 = 0.0004$ the value of the determent jumped to 125.

Proposed Solution

Two solution approaches are proposed to avoid the singular configurations. First approach is by using genetic algorithm technique to find alternative configurations to those singular configuration. So that the robot can follow the alternative free-singularity configuration path instead of moving through a path having a singular configuration. The second approach is to design avoidance function to forbid the robot movement toward the singularity so that the robot avoid the instability behavior in its motion. This designed function aims to control the motion of the joint around its singular value.

4.1 First approach: Genetic Algorithm for Alternative Configuration

Our goal is to find the alternative configurations to the singular configurations while ensuring that the error between the two configurations (singular and alternative) is minimized, as shown in figure 2.

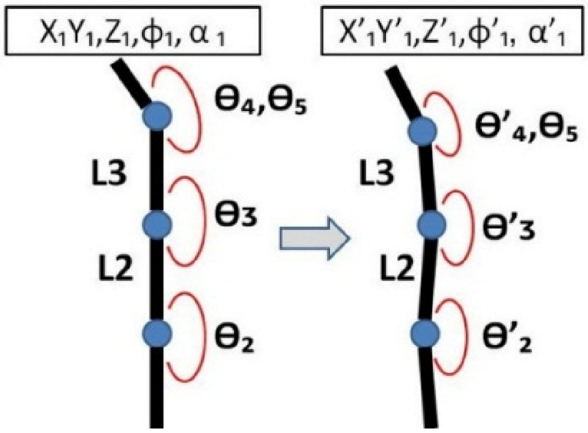

Figure 2: The alternative pose to singular pose with change in joints

By looking at any singular configuration, it is found that the joint configuration vector is $Q = (\theta_1, \theta_2, \theta_3, \theta_4\ , \theta_5)$, where θ_1 and θ_5 don't affect singularity, Therefore, the main concern is to control and optimize the error between the three angular joints (θ_2, θ_3 and θ_4). So, the dimension of the problem is reduced by considering the robot arm as a three degrees of freedom. As for in the Cartesian space the robot has only (x, z, α) to be controlled, where *x* and *z* are the Cartesian coordinates of the end-effector, and *α* is the pitch angle of the end-effector.

Objective Function: To design the optimization function that helps to avoid the singularity while keeping the robot end effector at the planed Cartesian position and in the same time minimize the change in the robot joint space. That is why there are two objective functions have to be optimized simultaneously. The first function considers the distance between the two configurations Q_1 and Q_1^* in the joint space where $Q_1 = [\theta_2, \theta_3, \theta_4]$ and $Q_1^* = [\theta_2^*, \theta_3 + 0.2^o, \theta_4^*]$, with the optimization function defined as:

$$f_J(\theta_2, \theta_4) = \sqrt{(\Delta\theta_2)^2 + (\Delta\theta_4)^2} \tag{5}$$

where $\Delta\theta_2 = \theta_2^* - \theta_2$ and $\Delta\theta_4 = \theta_4^* - \theta_4$.

The second function defines the error in the Cartesian space between P_1 and P_1^* where $P_1 = [X, Z, \alpha]$ and $P_1^* = [X^*, Z^*, \alpha^*]$, in this case the optimization function in Cartesian space is defined as:

$$f_C(X, Y, \alpha) = \sqrt{(\Delta X)^2 + (\Delta Y)^2 + (\Delta\alpha)^2} \tag{6}$$

where $\Delta X = X^* - X$, $\Delta Y = Y^* - Y$ and $\Delta\alpha = \alpha^* - \alpha$.

The main purpose for using GA optimization is to minimize the error in Cartesian space and also to minimize the difference in the joint space. To reach this requirement, a balancing parameter is added to combine the least square error in joint space and in the Cartesian space between the two configurations.

$$f_{JC}(\theta_2, \theta_4, X, Y, \alpha) = \lambda\, f_J(\theta_2, \theta_4) + (1-\lambda)\, f_C(X, Y, \alpha) \tag{7}$$

The genetic algorithm parameters values are set to be: elitism = 10%, cross-over = 80%, mutation = 10%, population size = 300 and the number of generation = 500. It is found that the optimized values of θ_2 and θ_4 for each case is equal to its value in the singular configuration minus the half of the value of θ_3. This means that if the value of θ_3 is 0.2^o then θ_2 will be $(\theta_2 - 0.1)$ and θ_4 will be $(\theta_4 - 0.1)$. The effect of changing λ on the error defined by both Cartesian space and joints space is also investigated. The total Cartesian error increased proportionally with λ, which indicates that the important parameter is to control the Cartesian error while the error in the joints space declines.

4.2 Second approach: Avoidance Task Function

An avoidance task function is introduced in the control system of the robot arm based on the results of the analytical study of robot singularity. The configuration space is divided into three zones named SAFE, CARE and STOP zones. The SAFE zone is when the robotic arm is operating very far from the singularity and in that case the avoidance function do nothing, the CARE zone is when the robotic arm is approaching the singular position but not yet reaching it, the last zone is the STOP zone is when the robot has to stop completely just before reaching the singular point. The zone parameter function is given in 8:

$$\widehat{\Psi}(\theta) = \begin{cases} 0 & if\ 5 \le \theta_3 & SAFE\ zone \\ \dfrac{\Psi(\theta_3) - \Psi(5)}{\Psi(0.2) - \Psi(5)} & if\ 0.2 < \theta_3 < 5 & CARE\ zone \\ 1 & if\ \theta_3 < 0.2 & STOP\ zone \end{cases} \tag{8}$$

Where

$$\Psi(\theta_3) = 1/(1 + \exp^{20*\frac{\theta_3 - 0.2}{5-0.2} - 10}) \tag{9}$$

The zone parameter function is then used to adopt the avoidance task which acts as a braking speed, using equation (10):

$$\mathrm{k}_3(\theta_3) = -\dot{Q}_3 * \widehat{\Psi}(\theta_3) \tag{10}$$

where $\mathrm{k}_3(\theta_3)$ is the output variable that stabilize the velocity of joint 3, $\dot{Q}_3$ is the velocity of joint 3 and θ_3 is the value of joint angle.

Therefor the operations of the system are defined by three main stages. Stage 1 is defined when θ_3 operates between 90 and 5 where no avoidance mechanism is required, corresponding to SAFE zone. Stage 2 is defined when θ_3 operates between 5 and 0.2 where the avoidance mechanism is activated and modify the main angular velocities to control the velocity of θ_3 to slow it down, corresponding to CARE zone. Last one is stage 3 is defined when θ_3 reaches 0.2, in this point the avoidance mechanism prevents any motion on θ_3 toward zero, corresponding to CARE zone.

Implementation of the Proposed Technique

As seen in previous sessions, the main singular configuration for CRS robot is when θ_3 tends to zero, Three experiments are performed, the first one is to study the robot behavior when the task is to move toward the singular configuration where no singularity avoidance task is considered. The second experiment is to apply the singularity avoidance task when the robot moves toward a singular configuration. The third experiment is to validate the results obtained from the genetic algorithm regarding the alternative poses corresponding to a pose at a singular configuration. Experiments one and two are planned such that the robot starts from the home position at which the joints configuration $[\theta_1, \theta_2, \theta_3, \theta_4, \theta_5] = [0, 0, 90, 0, 0]$ and moves towards the singularity at $\theta_3 = 0$.

Experiment 1: No avoidance algorithm is considered when performing this experiment. The main concern of this experiment is to test the effect on robot joints and motors when the performed task leads the robot to operate around a singular points. The robot is set to move under full joint speed, 5 deg/sec, and commanded to enforce joint θ_3 to reach its zero value. Results show an extreme motion of the robot arm especially in joints two, three and four. Joint 3 movement towards the singularity is illustrated in Figure 3, it is clear that once joint 3 reached the zero limit a huge movement is exerted on this joint so that θ_3 increased from $\theta_3 = 0^o$ to the joint limit of 130^o by moving in the opposite direction of the original movement in few milliseconds. The motor rates shows an incredible reverse motion when approaching the singular point, it is moving with almost 5 deg /sec with a steady increase till it reached almost 50 deg /sec in the neighborhood of the singular point. Then the motion is reversed in the opposite direction at a very high speed. The change in rates of motor 3 is shown in Figure 4, it is important to mention that the maximum allowed speed limit for motor 3 is 25 deg /sec and because of singularity the graph shows that for a very short period the motor rates reaches 250 deg /sec which is 10 times the allowed speed limit.

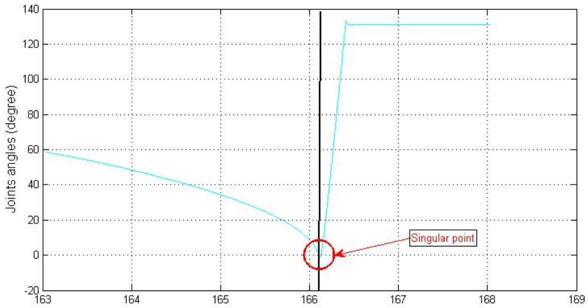

Figure 3: The motion of joint 3 towards singularity and the moment after

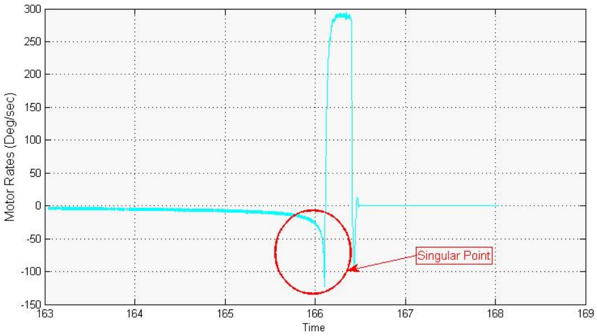

Figure 4: The rates of motor 3 responsible of the motion of the third joint.

The study of motion and the action of other joint was a necessity in this case, joints 2 and 4 have shown a more powerful reflection towards the singularity of joint 3 more than both joints 1 and 5, this may be due to an inner connection or dependence of motors of both joints 2 and 4. The behaviors of both joints are shown in Figure (5), it is clear that both joints are affected by the singularity of joint 3 which increase the sensitivity of this Arm robot toward this singularity. The motor rates for both joints show a great effect due to singularity especially in motor 2 which is illustrated in Figure (6). The effect is clear to be noticed so that it can be avoided later.

Studying joint 1 and joint 5, shows that there is no remarkable or significant effect on both joints due to the singularity whether in the value of joints nor in the motor rates. All effects occur at joint 1 and joint 5 after the singularity are illustrated in Figures (7) and (8).

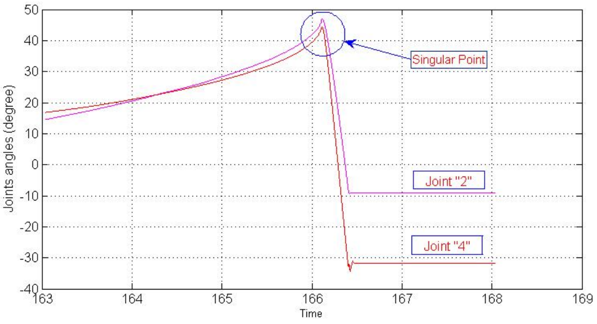

Figure 5: The joint movement of both joints 2 and 4

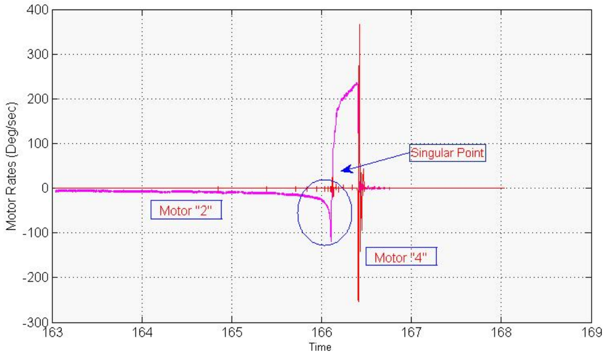

Figure 6: The rates of motors 2 and 4 during singularity of joint 3

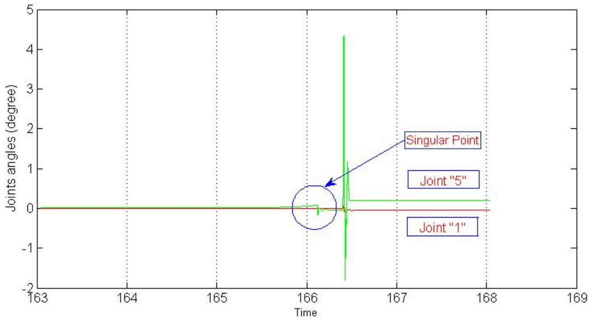

Figure 7: The joint movement of both joints 1 and 5

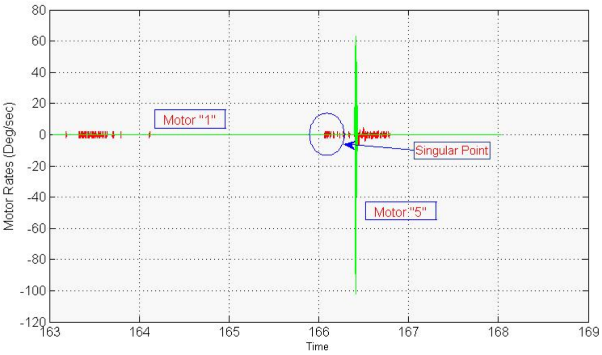

Figure 8: The rates of motors 1 and 5 during singularity of joint 3

Experiment 2: This experiment is performed to investigate the effect of applying the avoidance mechanism represented by Equation (10) on the system of CRS catalyst 5T arm robot. The behaviors of joints 2, 3 and 4 are illustrated in figure (9). It is clear that as soon as the value of θ_3 decreases and approaches 5^o, which is close to a singular configuration, the avoidance task is activated to forbid the robot from reaching its singular configuration at $\theta_3 = 0$. The behaviors shown by θ_2, θ_3 and θ_4 are different than the corresponding behaviors shown in the first experiment, where no avoidance is considered and undesirable velocity is presented. In figure (10), the main angular velocities $\dot{\theta}_2$, $\dot{\theta}_3$ and $\dot{\theta}_4$ are presented. The avoidance task does not affect the angular velocities of joint 3 before reaching the pre-defined threshold located at $\theta_3 = 5$. Just at iteration 534 the avoidance task is activated. It is clear that θ_3^* kept on decreasing which cause θ_3 to reach the second threshold value at $\theta_3 = 0.2$ in which the avoidance task forbids joint 3 from extra movement toward the singularity. As can be seen the motion of joint of joint 3 is smooth compared to the motion in experiment 1 thanks to activating the avoidance task. However the motion is stop as soon as it reach the second threshold.

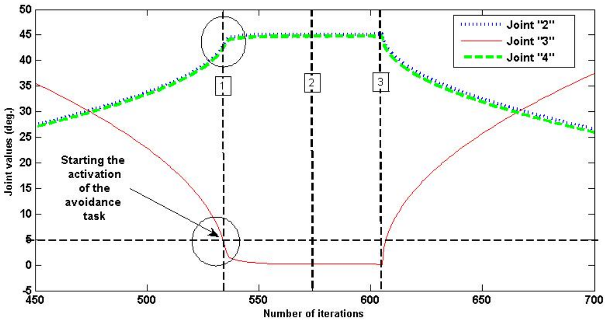

Figure 9: Values of $\boldsymbol{\theta_2}$, $\boldsymbol{\theta_3}$ and $\boldsymbol{\theta_4}$

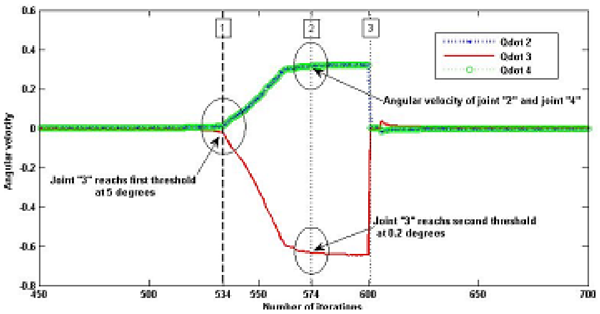

Figure 10: $\boldsymbol{\dot{\theta}_3}$, $\boldsymbol{\dot{\theta}_2}$ and $\boldsymbol{\dot{\theta}_4}$

Experiment 3: This experiment is performed validate the results obtained from the GA. The robot arm was moved between different positions. The configuration of robot position is set to simulate the values obtained from the GA. At the singular configuration [0, 50, 0, 80, 0], the pose between the camera and object is stored. Then, a list of different configuration was defined such that each configuration is the similar to the singular configuration, after adding a constant value to θ_3, and subtract the half of this value to θ_2 and θ_4. For example, the second configuration can be [0, 49, 2, 79, 0]. This procedure was repeated for θ_3 equal to 1, 2 , 10 and 20. The values can be seen in table (2).

Table 2: Validation of genetic algorithms results

Link	$\boldsymbol{\theta_3 = 0}$	$\boldsymbol{\theta_3 = 1}$	$\boldsymbol{\theta_3 = 2}$	$\boldsymbol{\theta_3 = 10}$	$\boldsymbol{\theta_3 = 20}$
X	428.1	428.1	428	426.6	422.22
Y	0	0	0	0	0
Z	547.9	547.9	547.6	456.61	542.9
∝	2.269	2.269	2.269	2.22691	2.269
∅	0	0	0	0	0
ψ	0	0	0	0	0

The six rows represent the Cartesian coordinates of the end effector. From the results in the table it we conclude that the results from the GA are correct and valid in the cases when small difference in θ_3 is considered. When a higher change in θ_3 is tested the error will increase in the end effector Cartesian coordinates.

Conclusion

In this paper the kinematic singularities of CRS catalyst 5T robot arm are studied analytically and numerically. The genetic algorithm is used to find alternative poses corresponding to the pose at singular configurations. A singularity avoidance mechanism is proposed to enhance the behavior of the system near singularities. Many experiments are performed on the real arm robot.

The results of the analytical study showed that the robot has three singular configurations, two of them are shoulder singularities at $\theta_2 = 135$ and at $\theta_4 = -45$ which are not in the configuration space of the robot while the third one is an elbow singularity at $\theta_3 = 0$ which is in the robot configuration space. The numerical results is coherent with the analytical results with respect to the singularity at $\theta_3 = 0$ which is the only discovered singularity in the work space.

The experimental tests are performed to study the effects of the singularity on CRS catalyst 5T robot arm by considering the joint movements and motor rates. The results show that the joint singularity affects other joints behaviors. As expected, approaching a singular configuration leads to instability in robot motion and can damage robot internal mechanisms which may leads to a catastrophic situations.

A singularity avoidance mechanism is developed based on Genetic algorithm optimization technique. This technique is used to optimize the final position of the end effector. The objective function is defined to minimize the error between the singular configuration and the available alternative positions. Both of the Cartesian error and joints space error are monitored and controlled by the objective function. The results obtained from the genetic algorithm are validated on the real robot. The singularity avoidance mechanism using alternative pose is tested through a real time experiments on the CRS arm robot and the singularity is avoided successfully when performing positioning tasks.

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