ON-ORBIT SERVICING: NOVEL ALGORITHMS FOR MOTION CONTROL OF ROBOT MANIPULATORS

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ABSTRACT

On-Orbit Servicing (OOS) involves assembly, repair and maintenance of satellites, space stations and platforms using robot manipulators. This is an emerging technology and there is a great demand to develop innovative, feasible and low-cost technology. Autonomous path planning and obstacle avoidance of the servicing robot arm is challenging and would require an intelligent on-board motion control algorithm. This paper presents a novel method for path planning and obstacle avoidance of robotics manipulators for on-orbit service tasks. Extensive simulation has been conducted for two classes of terrestrial arms, namely the six degree of freedom MELFA RV-1A arm and planar 3-RRR (revolute-revolute-revolute) manipulator. A modified 3-4-5 interpolating polynomial is used to plan a trajectory. A polynomial function which is smooth and continuous in displacement, velocity and acceleration is used to find smooth path avoiding the obstacles. An Artificial Neural Network (ANN) is implemented to solve the kinematics equations of manipulators to estimate the distance between gripper and obstacle. The proposed algorithm can be used for obstacle avoidance for a *priori* known obstacle as well as moving obstacles. The simulating results demonstrate the efficiency of the proposed algorithm.

Keywords: On-orbit servicing, Robot manipulators, Path planning, Hazard avoidance, Neural networks

INTRODUCTION

Path planning for a robotic manipulator for in-orbit servicing of satellites deals with finding an optimized trajectory from initial to final positions. The desired optimized trajectory should be as smooth as possible, i.e., abrupt changes in position, velocity, and acceleration should be avoided. While smooth motion can be implemented with simple techniques, there is no guarantee that no abrupt motion change will occur, because the work environment could be cluttered with objects. Many important contributions to this problem have been made in the last decade [1]-[6]. Ambike developed an approach to coordinate a two degree of freedom planar system via curvature theory to path tracking [1]. Dash presented a singularity-free path generation method to determine reachable workspace of a parallel manipulator [2]. Zhou analyzed singularity-free path generation capability of five-bar slider-crank parallel manipulators [3]. Bhattacharya proposed two on-line singularity avoidance schemes which restructure such a path of manipulator near singularity to keep the actuator forces always within their capabilities [4]. Dasgupta and Mruthyununjaya proposed an algorithm which finds safe path points and plans a continuous path (free of singularity) connecting initial positions to final posetions [5]. Merlet presented an algorithm to verify a trajectory for a six degree of freedom parallel manipulator with respect to the workspace, on the method, for two known posture of the end-effectors, the algorithm determines whether the straight line joining these two points in the parameter space lie completely within the work space [6].

Neural networks are reliable techniques to solve complex problems in robotics and are computationally fast. Neural networks have the ability to solve various complex problems. Moreover, they are fast and reliable. Karlik and Aydin applied a three layers neural network for solving forward kinematic of a serial manipulator [7]. Koker solved inverse kinematic problem of a 6 DOF arm which is based on using three neural networks designed parallel to minimize the error of the whole system [8]. Mayorga and Sanongboon presented an artificial neural network approach for fast inverse kinematics computation and effective geometrically bounded singularities prevention of redundant manipulator [9]. Koker and Oz used artificial neural networks for solving inverse kinematic problem of a three joint serial manipulator [10].

As on-orbit refueling, repair and maintenance of satellites will increase satellite lifetime dramatically and reduce the associated cost. This requires affordable and feasible technology to control the robotic manipulator mounted to the servicing spacecraft. The US Defense Advanced Research Project Agency (DARPA) and Europe Space Agency (ESA) have developed some advancement in this area [11]-[13]. For this application, the robot manipulator should be able to reach different parts of satellite for service, which will be accomplished through trajectory planning methods. Moreover, the arm should avoid any collision with different parts of the satellite such as solar panels that might be between manipulator and the damaged part. Therefore, path planning methods which involve comprehensive obstacle avoidance is useful for application of robotic manipulator for OOS.

In the proposed work, a modified 3-4-5 interpolating polynomial is used to plan a trajectory for every joint. Inverse Kinematics Problem (IKP) is solved to compute the all the joints angles in every step in order to evaluate the positions of gripper. An artificial neural network, which is trained by forward kinematics data, is implemented to solve IKP. In order to estimate the distance between gripper and any obstacle, the forward kinematics problem of the manipulator will be solved based on D-H transformation in every step of the desired path. It is possible to verify if collision occur by solving forward kinematics for joint angles in every step of trajectory and comparing the answer with obstacle position. In this case, smooth displacement function is added to one or more joints angles and this modification is continued until the gripper avoid obstacle thoroughly and attain the desired trajectory. The initial results of this paper are based on kinematic model of two terrestrial arms, which can be extended to a space free-flyer spacecraft with single or dual arm using its kinematics model for satellite servicing purpose.

TRAJECTORY PLANNING

For the proposed algorithm, trajectory planning is done from a given initial pose, specified by the position of one of its points and its orientation with respect to a certain coordinate frame, to a final pose, specified likewise; such that the motion is smooth and no collisions and singularities occur. Different approaches have been presented to solve collision free trajectory planning problems [14]-[16]. But, the majority of them have noticeable deficits such as implementing the free-of-obstacle part of workspace. This decreases the volume of workspace dramatically or lead to abrupt change in the velocity of the actuators whenever the gripper encounters an obstacle. Moreover, they cannot avoid any prior unknown obstacle easily and smoothly.

A polynomial interpolation based method is applied to plan a trajectory for every joint, which has some significant advantages over the simple ones with a higher degree such as those used by Lagrange interpolation [16]. It can be twice differentiated, and thus ensures the smoothness of the trajectory. In addition, it only requires a small number of conditional points to form the trajectory. Thus, we study trajectory planning with the aid of a fifth-order polynomial, $S(\tau)$ namely.

$$S(\tau) = a\tau^5 + b\tau^4 + c\tau^3 + d\tau^2 + e\tau + f \tag{1}$$

where a , b , c , d , e , f are constants which are found by recalling boundary conditions.

$$0 \le \tau \le 1 \quad , \quad 0 \le S \le 1 \tag{2}$$

It is assumed that the time is counted from the initial position, i.e., corresponding to $t = 0$. If the operation takes place in time T , then at the final position, $t = T$.

$$\tau = \frac{t}{T} \tag{3}$$

A normal polynomial that represents each of the joint variables θ_j throughout its range of motion is considered as:

$$\theta_j(t) = \theta_j^I + \left(\theta_j^F - \theta_j^I\right)S(\tau) \tag{4}$$

where θ_j^I and θ_j^F are the given initial and final values of the j th joint variable, respectively. In vector form, (4) becomes:

$$\boldsymbol{\theta}(t) = \boldsymbol{\theta}_I + \left(\theta_F - \boldsymbol{\theta}_I\right)S(\boldsymbol{\tau}) \tag{5}$$

It is thus possible to determine the evolution of each joint variable if both its end values and the time required to accomplish the motion is known. In the absence of singularities, then, the conditions of zero velocity and acceleration imply zero joint velocity and acceleration, respectively. With respect to initial and final conditions, the normal polynomial sought is:

$$S(\tau) = 6\tau^5 - 15\tau^4 + 10\tau^3 \tag{6}$$

This is called 3-4-5 polynomial. Through determining the number of steps and implementing (5) and (6) respectively, a set of $S(\tau)$, that result different angles for every joint in order to create a smooth trajectory, is planned.

The lack of guarantee for avoiding singularity region has turned the former method into unreliable approach. In order to alleviate this drawback, the distance between the gripper and any probable obstacle or singular point must be estimated via applying forward kinematics, which represents the end-effector cartesian positions with respect to joints values per different steps that are created through trajectory planning equations.

OBSTACLE AVOIDANCE

The polynomial trajectories discussed above only met the cartesian trajectories prescribed at the initial and final instants. If collisions and singularities occur, there is a need modify the trajectory so as to eliminate them, while keeping the trajectory as smooth as before. This is done by adding some smooth and continuous displacement functions to the polynomial (1). As shown in Fig. 1 and stated in (7)-(10), four half-cycloidal motions $S'(\tau)$ will modify the trajectory to eliminate any obstacle or singularity without any abrupt changes in the displacements, velocities and accelerations.

The equations of smooth function are:

$$S'(\tau') = L[\tau' - 1/(\pi \sin(\pi\theta'))] \quad , \quad 0 \le \tau' \le 1 \tag{7}$$

$$S'(\tau') = L[\tau' + 1/(\pi \sin(\pi\theta'))] \quad , \quad 1 \le \tau' \le 2 \tag{8}$$

$$S'(\tau') = L[1 - \tau' + 1/(\pi \sin(\pi\theta'))] \quad , \quad 2 \le \tau' \le 3 \tag{9}$$

$$S'(\tau') = L[1 - \tau' - 1/(\pi \sin(\pi\theta'))] \quad , \quad 3 \le \tau' \le 4 \tag{10}$$

where L is arbitrary constant.

Initially, a preliminary trajectory from the initial to the final position in the joint space is designed disregarding the obstacles and singularities. Then, collisions or singularities are verified. If this is the case, add $S'(\tau')$ to $S(\tau)$. Such that (5) takes the form:

$$\theta_j(\tau) = \theta_j^I + \left(\theta_j^F - \theta_j^I\right)[S(\tau) + S'(\tau')] \tag{11}$$

This modification is applied over one or more joints until the desired trajectory is obtained.

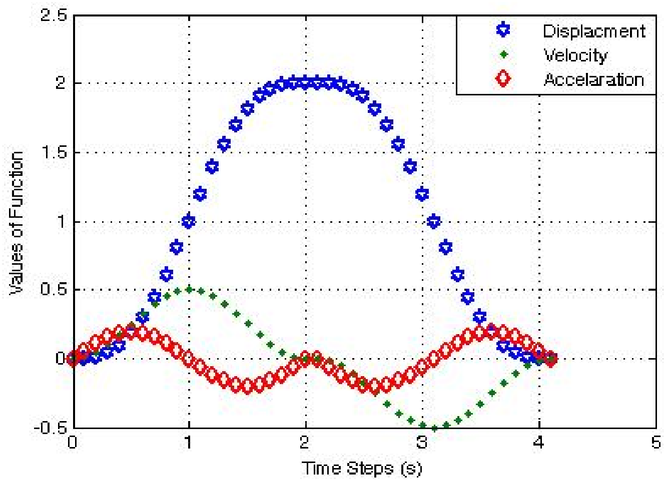

Fig. 1. Plot of function $S(\tau')$

The method presented guarantees no sudden changes in velocities and accelerations in the joint space during changing the desired path for obstacle avoidance. Moreover, the gripper will come back to the desired trajectory after avoiding obstacles which guarantee the optimum trajectory.

SIMULATION RESULTS

Planar 3-RRR Manipulator

The planar 3-RRR manipulator shown in Fig. 2 has three revolute joints. The manipulator consists of a kinematic chain with three closed loops, namely M_1DABEM_2, M_2EBCFM_2 and M_3FCADM_1, where the gripper is attached to triangle ABC [17]-[21]. It is assumed here that the manipulator is symmetric, and therefore, all the motors will be placed on the vertices of the fixed equilateral triangle. The forward kinematics deals with motion of end-effector of the robot according to the world coordinate system. For parallel manipulators, in general, this is a system of nonlinear algebraic equations.

In this paper ANN, is implemented to solve the forward kinematics of planar 3-RRR parallel manipulator. Firstly, some known points of the workspace of manipulator are taken. By solving inverse kinematic problem, the joint angles $(\theta_1, \theta_2, \theta_3)$ corresponding to different (X, Y, ϕ) cartesian coordinates are computed. These values are recorded in a file to form the learning set of neural network. With respect to the rule which claim that the inverse kinematic problem of the 3-RRR planar manipulator admits eight sets of solutions [19], eight sets of training file are constructed. Around 5000 different positions of gripper in nearly all over the workspace are used. Four thousand of these data were used in training of neural network, and the rest were used in testing. Eight multi layer perceptron neural networks were designed separately and each one includes one hidden layer with 12 neurons and Tansig functions as transfer function. The learning rate set 0.1 and momentum constant was 0.9. The transfer function for input layer set Tansid and for out put layer set Purelin. The training procedure was completed approximately in 30,000 iterations. Back propagation algorithm was implemented and the error at the end of learning process is bounded to 10^{-6} for the training sets. Every set of inverse kinematic answers was applied as a training set individually. So, eight neural networks are available for solving the forward kinematic problem. In order to solve forward kinematics, first, the input data (motors' angles) must be labeled to branch of an inverse kinematic problem. Then, motors' angles will present to the neural network which was trained with that set of inverse kinematic data. Finally, the trained neural networks can be tested by choosing some points within its workspace which did not used in the training process. After presenting the points to the completed neural network, the answers of neural network are compared with those from the inverse kinematic problems. The simulation results in Fig. 3 reveal the accuracy of the method. The plots of displacement, angular velocity and acceleration for *a priori* unknown obstacle for planar 3-RRR manipulator are shown in Fig. 4 to Fig. 7.

MELFA RV-1A Arm

The MELFA RV-1A arm robot shown in Fig. 8 has six degree of freedom, and all of its joints are rotational. The forward kinematics representation is established using D-H notation [22]. In order to solve Inverse Kinematics Problem, an A.N.N designed similar to FK of planar 3-RRR. The changes of joints' variables and an example of arm obstacle avoidance are shown in Fig. 9 to Fig. 15. As the motion of the end-effector is supplied through turning of more than one motor, it is not necessary to add $S'(\tau')$ to (6) for every joints. For instance, in the applied test for MELFA RV-1A, no change has been imposed on the trajectories of joint 5 and the joint 6. On the other word, the value of $S'(\tau')$ is equal to zero for these two joints. In some other cases such as joint 1 of the 3-RRR planar manipulator, $S'(\tau')$ will be exposed with negative sign. Based on Fig. 4 the displacement of joint 1 decreased during the obstacle avoidance process. The value of this modifier term reaches through try and error.

For the obstacle avoidance scenario considered here, the MELFA RV-1A arm encounters an obstacle in the 8th step of trajectory. Therefore, the algorithm modifier commences modifying the paths of joint 1, joint 2, joint 3, and joint 5 and derives the arm back to predesigned trajectory using the method earlier after successfully avoiding the obstacle. Based on Fig. 9 to Fig. 14, the manipulator backs to prior path at 12th step.

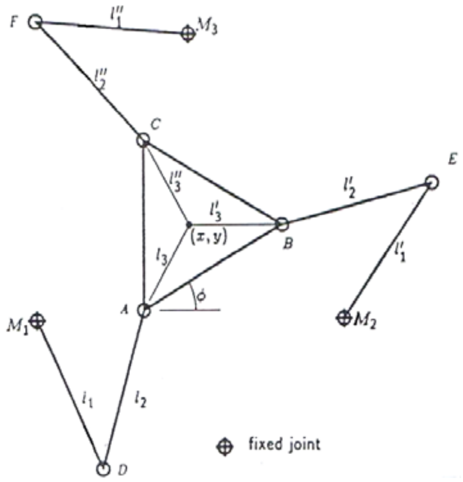

Fig. 2. Planar 3-RRR manipulator

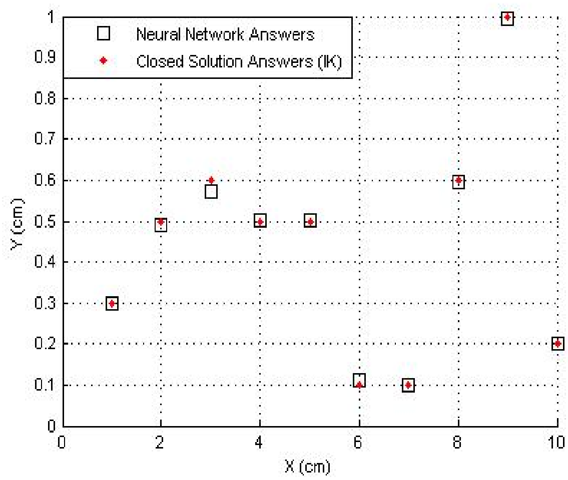

Fig. 3. Comparison between A.N.N and analyzed solution

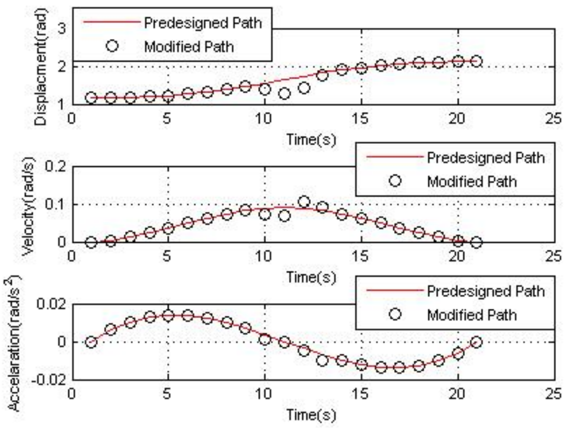

Fig. 4. Displacement, Angular Velocity and Acceleration of

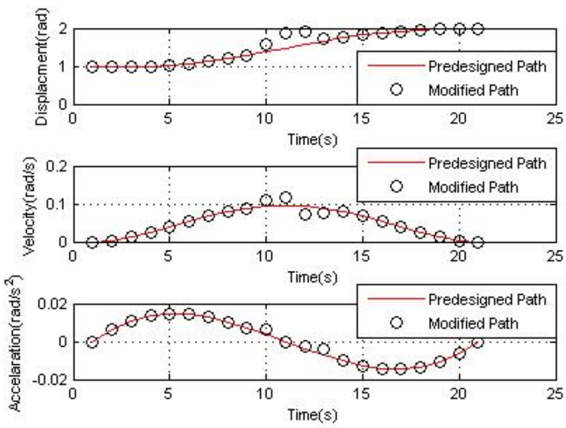

Fig. 5. Displacement, Angular Velocity and Acceleration of

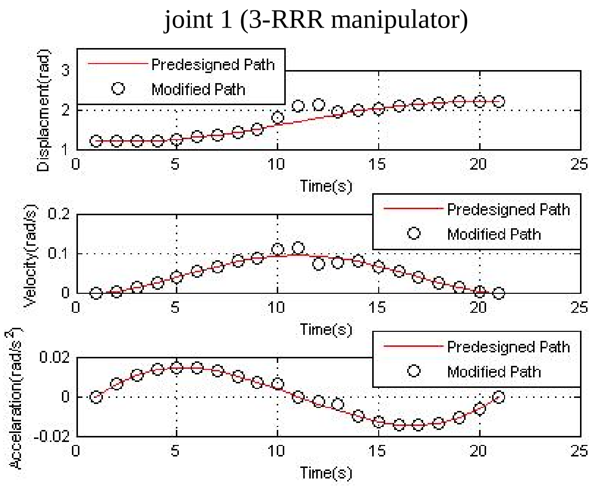

Fig. 6. Displacement, Angular Velocity and Acceleration of joint 3 (3-RRR manipulator)

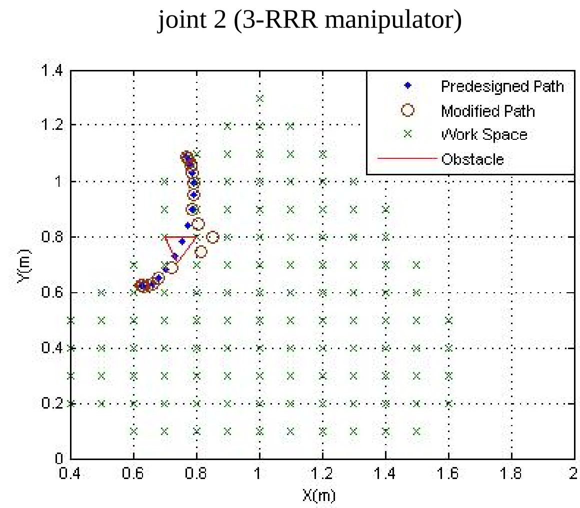

Fig. 7. Planar 3-RRR manipulator obstacle avoidance

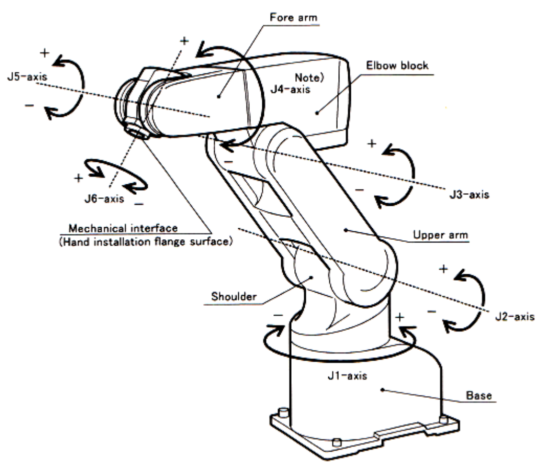

Fig. 8. MELFA RV-1A manipulator

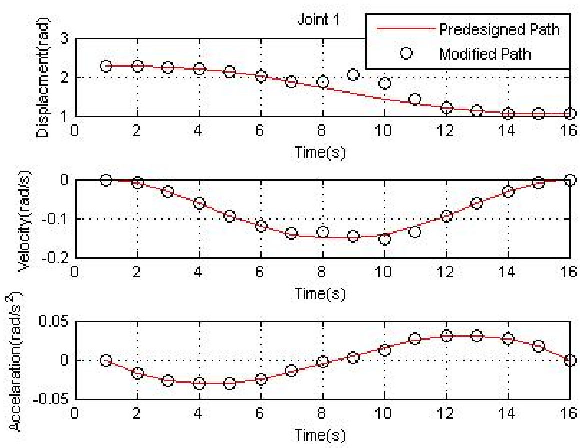

Fig. 9. Displacement, Angular Velocity and Acceleration of joint 1 (MELFA RV-1A arm)

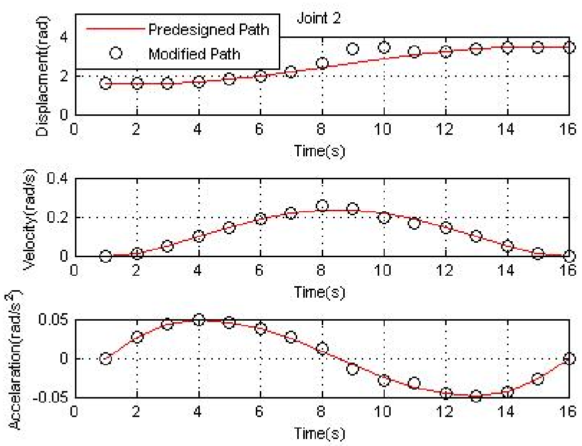

Fig. 10. Displacement, Angular Velocity and Acceleration

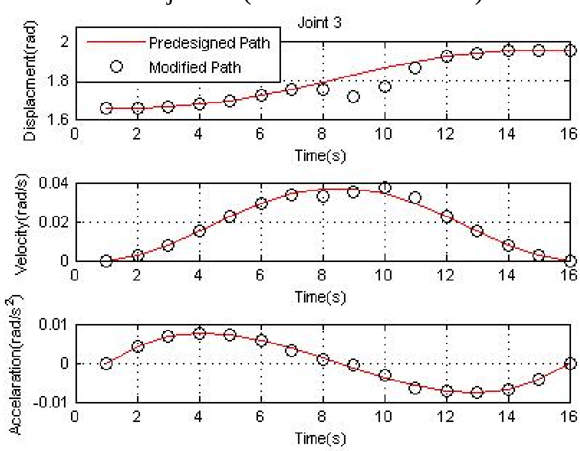

Fig. 11. Displacement, Angular Velocity and Acceleration

of joint 2 (MELFA RV-1A arm)

of joint 3 (MELFA RV-1A arm)

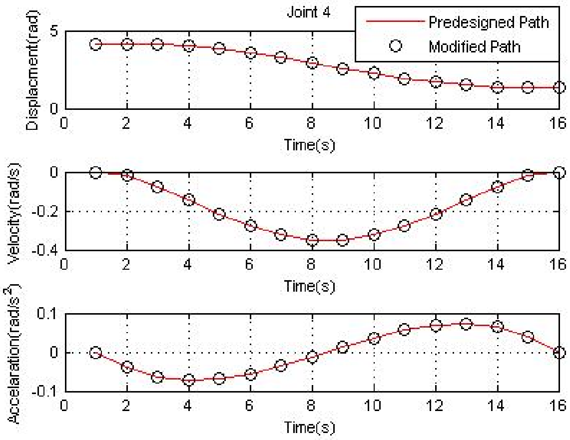

Fig. 12. Displacement, Angular Velocity and Acceleration of joint 4 (MELFA RV-1A arm)

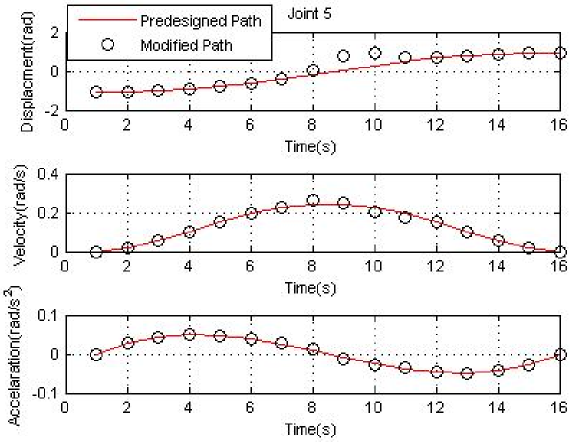

Fig. 13. Displacement, Angular Velocity and Acceleration of joint 5 (MELFA RV-1A arm)

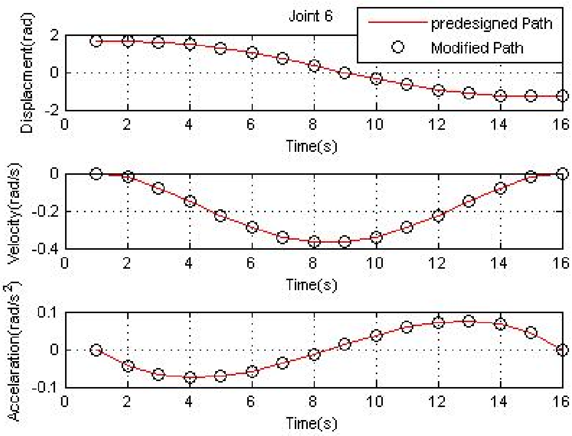

Fig. 14. Displacement, Angular Velocity and Acceleration of joint 6 (MELFA RV-1A arm)

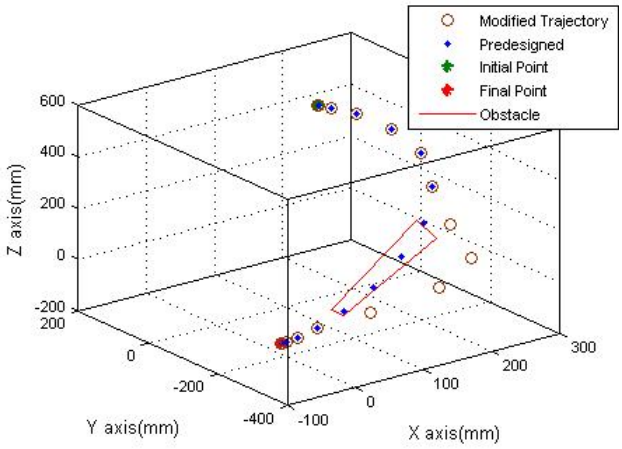

Fig. 15. MELFA RV-1A obstacle avoidance

CONCLUSION

A simple and efficient algorithm for robot manipulator trajectory planning and obstacle avoidance is presented in this paper. This method yields very smooth collision-free trajectories that drive the gripper from an initial to final desired position, even if the gripper encounters an obstacle. The presented method prevents abrupt changes in velocities and accelerations in the joint space during changing the desired path for obstacle avoidance. The simulation results prove that this algorithm is efficient and accurate and is suitable for both serial and parallel manipulators to perform different assembly and servicing tasks. This path planning and obstacle avoidance algorithm can be extended to free-flyer servicing spacecraft with dedicated attitude control. These applications are under investigation.

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