

Modeling and Validation of Rapid Prototyping Related Available Workspace

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ABSTRACT

Path planning and re-planning for serial 6 degree of freedom (DOF) robotic systems is challenging due to complex kinematic structure and application conditions which affects the robot's tool frame position, orientation and singularity avoidance. These three characteristics represent the key elements for production planning and layout design of the automated manufacturing systems.

The robot trajectory represents series of connected points in 3D space. Each point is defined with its position and orientation related to the robot's base frames or predefined user frame. The robot will move from point to point using the desired motion type (linear, arc, or joint).

The trajectory planning requires first to check if robot can reach the selected part(s). This can be simply done by placing the part(s) inside the robot's work envelope. The robot's work envelope represents a set of all robots' reachable points without considering their orientation. To visualize the robot's work envelope many available tools can be used.

It is common that some of the accessible points cannot be reached with the desired tool orientation. For accurate and optimal robot path generation, a visualization of the predetermined regions related to the application is highly needed. These regions are named robot work window.

In this paper, the work window has been calculated for the Fanuc LR Mate 200ic robot and the rapid prototyping application. The visual representation of the work window has been done using MATLAB tools and evaluated using the Fanuc LR Mate 200ic robot which is available in our lab.

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INTRODUCTION

In today's manufacturing scenario, product life cycles are decreasing and customers are demanding cheaper and high quality products in a timely manner. To satisfy a variety of customer needs, companies need to introduce the option of customizability to their portfolio by making their products and automated production in the reconfigurable manner.

Reconfigurable Manufacturing Systems (RMS) are identified as a means of improving the production outcome by quickly adjust its production capacity and functionality in response to sudden market changes and needs, [1]. The RMS require design tool that will allow the automated production to quickly configure and reconfigure.

The automatic machines, such as robots are constructed with various parameters like number of degrees of freedom, link length, link offset, joint types, payload, accuracy, workspace,

singular space, etc., which are key elements for the work cell layout design. The kinematic related parameters are used for calculating the machinery Workspace, Singularity and Work Window related to the machine's path.

To achieve the above said characteristics, effective and robust systems are required. It is important to know whether the robot end-effector can reach a particular point in its workspace at a desired orientation to allow modification or change in the placement or configuration before setting up the robot on the shop floor.

The 'boundary of space' model representing all possible positions which may be occupied by a mechanism during its normal range of motion (for all positions and orientations) is called the work envelope. In the robotic domain, it is also known as the robot operating envelope or workspace [2]. Several researchers have investigated workspace boundaries

for different degrees of freedom (DOF), joint types and kinematic structures utilizing many approaches [3, 4, 5, 6]. A recent example utilizes a reconfigurable modeling approach, where the 2D and 3D boundary workspace is created by using a method identified as the Filtering Boundary Points (FBP) algorithm, [7]. In [8], the authors first defined the work window as the functional subset of the work space. Previous research investigations were conducted on developing Jacobian by using different methods, [9]. These methods were compared in terms of their computational efficiency since the Jacobian must be computed in real time for control. Using three different methods for calculating Jacobian of 6 DOF robots with rotary of sliding joints are presented by [10] and applied on the PUMA robot. By employing symbolic reduction techniques in conjunction with the separation of the resultant equations into on-line, temporary variables and off-line constraints, efficient formulations of the Jacobian, inverse Jacobian, and inverse Jacobian multiplied by a vector have been developed by [11]. Jacobian can be obtained by simple method explained in reference [12]. The study and resolution of singularities for PUMA robot were analyzed in details by [13, 14, 15]. An important step for robot singularity analysis is task decoupling. This concept has been known since Pieper's pioneering work, [16]. The complete analysis of task decoupling was done by [17].

The calculation of the work window with the fixed tool frame and without any validation procedure has been previously done for FANUC S430IF, ABB IRB 6400-24 and KUKA KR-15/2 by [18, 19, 20]. This paper presents continuation of this research.

Currently, this reach problem is solved by visual inspection, different simulation packages, or by manually operating a teach pendant and by visually analyzing the workspace of the robot. In this research the work window has been calculated for the Rapid Prototyping application where the tool is always oriented such that the approach vector is pointing perpendicular to the floor. The sliding and normal vectors lay on the surface perpendicular to the approach vector and they satisfy the right hand rule.

The kinematic model of the FANUC LR Mate 200iC robot is first developed and validated using the data from the Teach Pendant. Base on this model, the Work Window is calculated. In the validation procedure several significant points were created by the Teach Pendant. The same points are created with the Matlab tools using the novel equations. Both methods generate the same outcomes, which mean that the Work Window is valid.

FANUC LR MATE 200iC KINEMATIC MODELING AND VALIDATION

A serial link manipulator connects the end-effector frame to the robot base frame, with each link connected to the next by an actuated joint. The FANUC LR Mate 200iC robot kinematic diagram is shown in Figure 1.

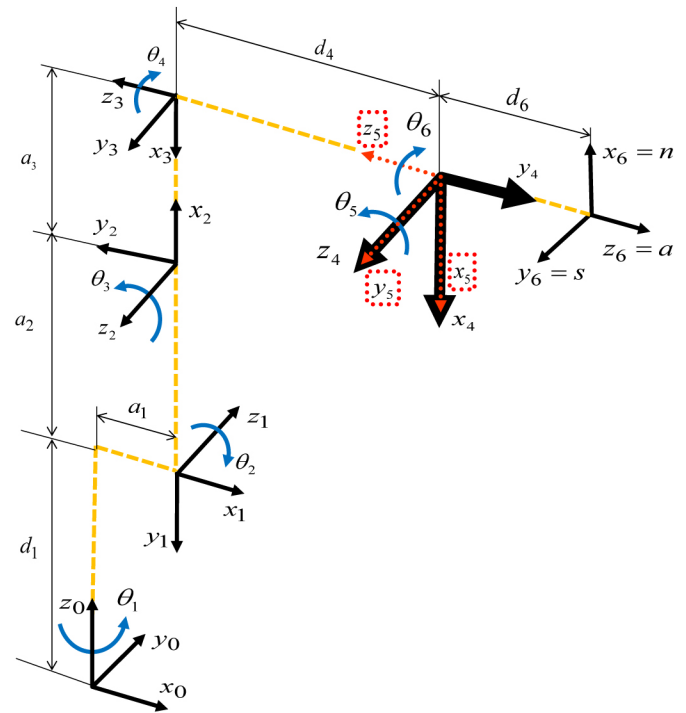


Figure 1. FANUC LR Mate 200iC robot kinematic diagram

If a coordinate frame is attached to each link, the relationship between two links can be described using Denavit and Hartenberg rules [21] and the four related parameters presented in Table 1. These parameters are a_i (i^{th} Link offset), d_i (i^{th} Link length), α_i (i^{th} Twist angle), θ_i (i^{th} Joint angle)

Table 1. D-H parameters for Fanuc LR Mate 200iC

JOINT	d_i	θ_i	a_i	α_i
1	$d_1 = 330$	$\theta_1 = 0^\circ$	$a_1 = 75$	$\alpha_1 = -90^\circ$
2	0	$\theta_2 = -90^\circ$	$a_2 = 300$	$\alpha_2 = 180^\circ$
3	0	$\theta_3 = 180^\circ$	$a_3 = -75$	$\alpha_3 = 90^\circ$
4	$d_4 = -320$	$\theta_4 = 0^\circ$	0	$\alpha_4 = -90^\circ$
5	0	$\theta_5 = 0^\circ$	0	$\alpha_5 = 90^\circ$
6	$d_6 = -80$	$\theta_6 = 180^\circ$	0	$\alpha_6 = 180^\circ$

The FANUC LR Mate 200iC robot kinematic model is validated by calculation of several selected points in 3D space and comparison of the same points using the robot Teach Pendant. The position and orientation of the i^{th} frame coordinate can be expressed in the $(i-1)^{th}$ frame by the following homogeneous transformation matrix:

$${}^{i-1}A_i = \begin{bmatrix} \cos\theta_i & -\cos\alpha_i \sin\theta_i & \sin\alpha_i \sin\theta_i & a_i \cos\theta_i \\ \sin\theta_i & \cos\alpha_i \cos\theta_i & -\sin\alpha_i \cos\theta_i & a_i \sin\theta_i \\ 0 & \sin\alpha_i & \cos\alpha_i & d_i \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (1)$$

The robot can now be kinematically modeled by using the link transforms:

$${}^0A_n = {}^0A_1 {}^1A_2 {}^2A_3 \dots {}^{n-1}A_n \quad (2)$$

Where ${}^0A_n$ is the pose of the end-effector relative to the base. ${}^{i-1}A_i$ is the link transform for the i^{th} joint; and n is the number of links. For the FANUC LR MATE 200iC robot, six homogeneous transformation matrices have been developed using Maple 16 symbolic manipulation software. The pose matrix of the end-effector relative to the base is presented in Equation 3.

$${}^0A_6 = \begin{bmatrix} n_x & s_x & a_x & p_x \\ n_y & s_y & a_y & p_y \\ n_z & s_z & a_z & p_z \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (3)$$

The end-effector orientation is defined with the rotation matrix in Equation 4.

$${}^0R_6 = \begin{bmatrix} n_x & s_x & a_x \\ n_y & s_y & a_y \\ n_z & s_z & a_z \end{bmatrix} \quad (4)$$

The orientation of the end-effector, relative to the robot base frame is defined with the three vectors: n , s and a (normal, sliding and approach).

The FANUC LR MATE 200iC robot World frame and Tool frame positions and orientations are calculated using the Matlab software, and graphically presented in Figure 2.

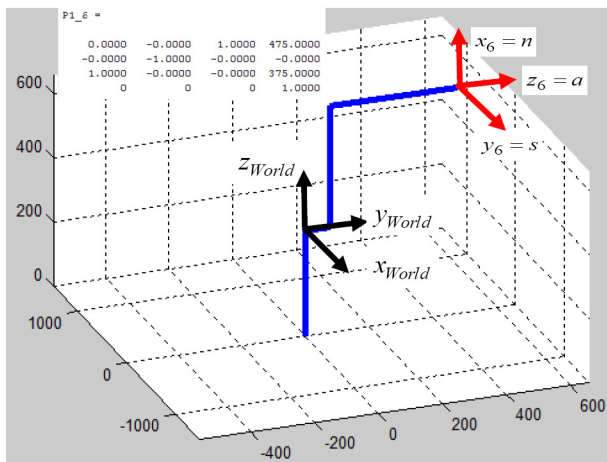


Figure 2. FANUC LR Mate 200iC robot world tool frames position and orientation

The first step in the procedure of robot kinematic validation is to check the robot world and tool frame position and orientation. The home zero position is created to verify the position and orientation of the end-effector frame relative to the robot predetermined world frame. See Figure 3. By the visual comparison between the Figure 2 and Figure 3 it is clear that the calculated home zero position is valid.

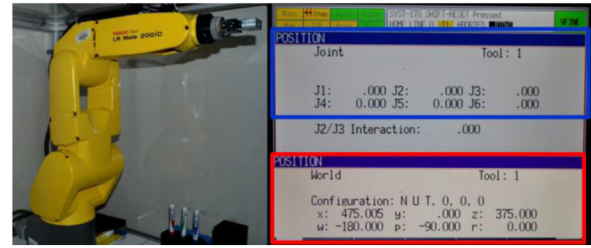


Figure 3. FANUC LR Mate 200iC robot home zero position

Another point is created and used for the kinematic model validation. See figure 4.

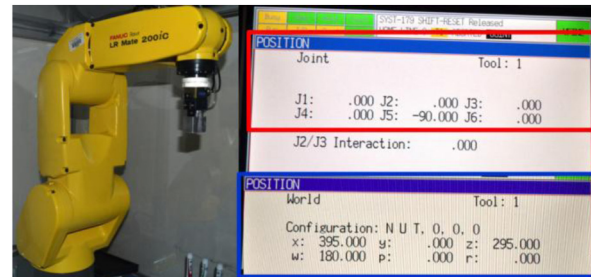


Figure 4. FANUC LR Mate 200iC robot selected point position and orientation

The Matlab program outcome confirms that the model is valid. See Figure 5.

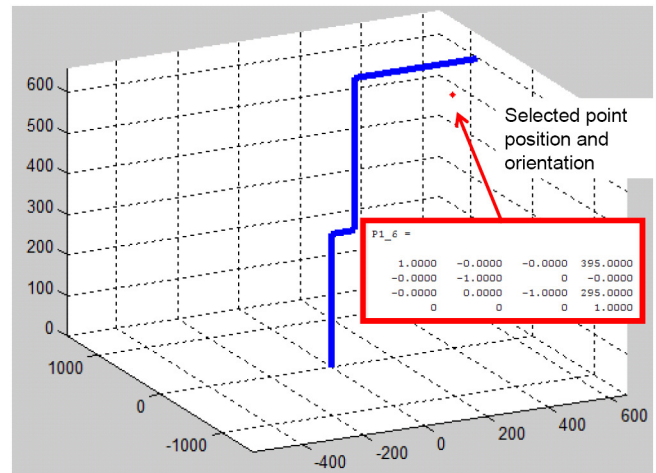


Figure 5. FANUC LR Mate 200iC robot selected point position and orientation calculate with Matlab software

To confirm the correctness of the frame orientation, the roll-pitch-yaw angles are calculated using the rotation matrix given in equation (5).

$$R = \begin{bmatrix} \cos \gamma \cos \beta & \cos \gamma \sin \beta \sin \alpha - \sin \alpha \cos \alpha & \cos \gamma \sin \beta \cos \alpha + \sin \gamma \sin \alpha \\ \sin \alpha \cos \beta & \sin \gamma \sin \beta \sin \alpha + \cos \gamma \cos \alpha & \sin \gamma \sin \beta \cos \alpha - \cos \gamma \sin \alpha \\ -\sin \beta & \cos \beta \sin \alpha & \cos \beta \cos \alpha \end{bmatrix} \quad (5)$$

The calculation procedure for the roll-pitch-yaw angles is given in Figure 6.