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Modeling of Multi-DOF Robotic Manipulators using Sim-Mechanics Software

Shiv Manjaree* **and Mitsu Thomas**

Department of Mechanical Engineering, TheNorthCap University, Gurugram – 122017, Haryana, India; shivmanjree@gmail.com, mitsut25@gmail.com

Abstract

Objectives: This paper presents a simulation based software platform to model and design a multi-degree of freedom robotic manipulator. **Methods:** Traditional methods of modeling robotic manipulators are a very laborious, iterative and time consuming task. In the last few years, new approaches towards the study of complex architectures of robotic manipulators have developed rapidly. In this paper, a new method based on Sim-Mechanics software is presented to simulate and design a multi-DOF robotic manipulator. **Findings:** It can be seen that the new software based method provides a much easier and faster way of modeling the multi-DOF robotic manipulator as compared to mathematical modeling. **Improvements:** The model developed using Sim-Mechanics software will be further used for dynamic analysis.

Keywords: DOF, Dynamics, Modeling, Robotic Manipulator, Sim-Mechanics

1. Introduction

In today's time, multi-DOF robotic manipulators have become an integral part of industrial applications. A variety of industrial tasks such as welding, spray painting, pick and place operation, assembly etc. are performed with the help of multi-DOF robotic manipulators. Any industrial application also highlights the importance of mathematical modeling of used multi-DOF robotic manipulators. Kinematic analysis and dynamic analysis is used for mathematical modeling of complex architectures of any multi-DOF robotic manipulators. Kinematic analysis of robotic manipulator is performed in two ways viz. forward kinematics and inverse kinematics. The forward kinematic analysis of any multi-DOF robotic manipulator is an easy task due to the presence of Denavit-Hartenberg convention. The inverse kinematics analysis is complex due to the availability of multiple solutions of joint variables. Research papers show that the Denavit-Hartenberg convention[1] was proposed in the year 1955 and since then a lot of work related to kinematic analysis has been done. Literature search shows that the maximum number of work has been done to perform the kinematic analysis of different multi-DOF robotic manipulators[2,3]. Software packages for educational purpose[4,5] have been developed based on kinematic analysis of multi-DOF robotic manipulators. The authors[6] have presented the kinematic results with experimental proofs for known trajectories of a 3-DOF Phantom Omni robot. Two different kinematic schemes[7] have also been compared to capture geometric primitives for an anthropomorphic manipulator.

Due to the iterative, non-unique and time consuming nature of inverse kinematic analysis, various hybrid and non-hybrid artificial intelligent techniques have been researched in past few years. A neuro-fuzzy based solution to the inverse kinematics problem of a 3-DOF planar robot[8,9] has been investigated. By using the ability of adaptive neuro-fuzzy technique to learn from training data, it is possible to create a representative fuzzy inference system using a back propagation neural network-like structure, with limited mathematical representation of the system[10]. Computer simulations have been conducted on 2-DOF and 3-DOF robotic manipulator to show the effectiveness of the approach. A comparative analysis has been carried out for inverse kinematic solutions obtained

** Author for correspondence*

for a 5-DOF industrial robotic manipulator using analytical calculations and hybrid artificial intelligent techniques with experimental validation[11]. The adaptive neuro-fuzzy technique has been applied on redundant robotic manipulators for the prediction of inverse kinematic solutions[12]. The inverse kinematic solutions for different multi-DOF robotic manipulators of surgical importance[13] have been obtained using neural network based artificial intelligent techniques. Multilayer feed forward networks and hybrid neuro-fuzzy artificial intelligent technique[14–17] has been applied to a 3-DOF robotic manipulator inverse kinematic problem. The repetitive trajectories[18] are tracked in the simulations made on the 3-DoF planar and 4-DoF spatial manipulators respectively and two optimization methods with joint limits avoidance are considered. The effectiveness of the proposed algorithm has been verified by simulation results and detailed comparative analysis among different methods and cases has been given. The performance of iterative algorithm for a 3-DOF crane[19] has also been investigated.

For any industrial application, dynamics of robotic manipulators play a vital role. Dynamic analysis of multi-DOF robotic manipulators can also be performed in two ways viz. forward dynamics and inverse dynamics. In forward dynamics, the movement of multi-DOF robotic manipulators due to the exerted force is investigated. In inverse dynamics, the forces causing the motion of end-effector of multi-DOF robotic manipulators are investigated. Several research works shows the mathematical formulation of dynamic analysis of multi-DOF robotic manipulators[20,21]. Various artificial intelligent techniques have also been used to ease the complexities involved in dynamic analysis of robotic manipulators. Hybrid artificial intelligent techniques based on fuzzy logic and neural networks have been investigated for the dynamic performance of different multi-DOF robotic manipulators[22–24]. Lagrangian approach[25] is used to derive the dynamic model of the structure. Links are modeled as Euler-Bernoulli beams with proper clamped-mass boundary conditions. Dynamic analysis[26] using Lagrangian's and Newton's Euler approach is worked out analytically using MATLAB. Two different neuro-fuzzy controllers[27] have been modeled and compared with PID controller for trajectory tracking control of 2-DOF robot manipulator. The modeling and simulation of 6-DOF bipedal robot[28] has been carried out. A brain controlled robotic wheelchair[29] has been modeled and simulated for elderly and disabled people. The effect of processing variables on fatigue life, impact energy and bead penetration of AA6061 joints produced by MIG robotic welding process[30] has been analyzed.

Along with kinematic analysis and dynamic analysis of multi-DOF robotic manipulators, the simulation of complex architectures of multi-DOF robotic manipulators using simulation software is also gaining importance. The advantage of using simulation software is that it helps in better visualization and understanding of the working of the multi-DOF robotic manipulator in a virtual world. The simulation software helps in avoiding the complexities involved in the mathematical formulations needed for both forward analysis and dynamic analysis. However, literature search shows that the work in this area is very limited and needs more focus to be paid. A systematic representation of mathematical and software for the effective simulation of mechanical system with Simulink dynamic simulation environment is given[31–33]. A method to model the mechanics of robot manipulators[34] is given. A simple and reliable approach to create a humanoid robot with Sim-Mechanics and VRML[35] is presented.

Traditional methods of dynamic modeling of multi-DOF robotic manipulators have been compared with a novel simulation method for physical modeling using Sim-Mechanics software and some interesting mathematical aspects of Sim-Mechanics software implementation have been examined. An effective approach to the physical modeling of multi-DOF robotic manipulator and its dynamic simulation using Sim-Mechanics software[36] has been given. A multi-body system[37] has been simulated with Sim-Mechanics.

In this paper, Sim-Mechanics software has been used to model the 2-DOF planar and 3-DOF planar robotic manipulators. In order to verify the model, the Sim-Mechanics block model obtained for multi-DOF robotic manipulators have been simulated to get the variations of reaction force and reaction torque acting on the robotic manipulator. The results presented in the later section show the proper design and development of 2-DOF planar and 3-DOF planar robotic manipulators on the Sim-Mechanics software.

1.1 About Sim-Mechanics

Dynamic simulation of multi-DOF robotic manipulators is a common problem in engineering sciences. Several programs available for dynamic simulation are either based on symbolic representations or dynamic equations of motion are solved. Certain numerical programs are also available which helps in dynamic simulation using 3D-SolidWorks model. Sim-Mechanics software falls in the last category.

Sim-Mechanics software helps in building a mechanical system virtually with the help of block diagrams. This software uses the standard Newtonian forces and torques acting on the system. Mechanical systems or multi-DOF robotic manipulators are represented by connected block diagrams. In Sim-Mechanics software, the complete multi-DOF robotic manipulator can be represented graphically in the form of blocks which in turn saves time and effort to model the robotic manipulator mathematically. The other advantages of using Sim-Mechanics software is that it helps to model, simulate, make changes in the system and system parameters and also analyze the results in a single environment itself. For physical modelling, the kinematic relationships and geometric relationships are directly mapped in Sim-Mechanics software. This feature saves a lot of time and efforts involved in deriving the dynamic equations of motion. The other feature of Sim-Mechanics software is that Sim-Mechanics blocks can be very easily interfaced with Simulink blocks. This feature helps the used to design the complete system in a single environment. Sim-Mechanics software comprises of different analysis modes and advanced visualization tools; making the complex dynamic simulations a very easy task. Any multi-DOF robotic manipulators can be analysed in four modes using the Sim-Mechanics software:

Forward dynamics command – It helps in calculating the motion of the mechanism resulted due to applied torques/forces.

Inverse dynamics command – It helps in calculating the torques/forces which are responsible to produce motion of any open loop mechanism.

Kinematics command – It performs the same task by considering extra internal constraints for any closed loop system.

Trim command – It helps in finding the starting point for any linearization analysis for a steady state motion of any system.

To implement a model in Sim-Mechanics software, a .mdl file is created better called as model. The Sim-Mechanics software contains ‘blocks’ in the library and other Sensor blocks and Actuator blocks used for interfacing Sim-Mechanics software with Simulink. Any mechanical system is modelled using ‘blocks’ which have elements representing rigid bodies connected with rotational or translational joints. For any particular joint, its position, velocity and acceleration are measured using joint Sensor blocks. The reaction force and reaction torque acting across the joint is also measured using joint Sensor blocks. The development of the dynamic model of a robotic manipulator starts with the identification of technical parameters either provided by the manufacturer or calculated manually. For using Sim-Mechanics software, the modelling of joints and other rigid parts is firstly done in the SolidWorks software. The modelling in SolidWorks software helps in creating an animation of the mechanical system or multi-DOF robotic manipulator; which in turn verifies the correctness of kinematic modelling of the multi-DOF robotic manipulator or given mechanical system. The model which contains mass, centre of inertia, tensor and graphics used for better visualization is then imported into the Sim-Mechanics software. The rigid bodies are used as simple blocks and have their time response lying within acceptable boundaries. The steps followed to model a multi-DOF robotic manipulator are as given below:

Technical specifications of sub-parts of rigid bodies i.e. inertia, DOF, centre of gravity etc. along with coordinate system needed to measure position and velocity at any point of time.

Applying forces/torques to obtain robot motions and complete the model with the help of sensors and actuators.

Simulate using Simulation solvers to find robot motions while maintaining any constraint applicable on the system.

Visualization of the multi-DOF robotic manipulator or any mechanical system while building the model.

Animation of the multi-DOF robotic manipulator or any mechanical system by simulating it using Graphical User Interface.

In this paper, 2-DOF planar and 3-DOF planar robotic manipulators have been modelled using Sim-Mechanics software.

1.2 Modeling of 2-DOF Planar Robotic Manipulator

In this section, a 2-DOF planar robotic manipulator has been considered. The SolidWorks model for 2-DOF planar robotic manipulator is shown in Figure 1. Each component of the robotic manipulator i.e. base, links and end-effector were modeled separately and assembled in SolidWorks software to get the required output. The description of movement of robotic manipulator is given in Table 1.

The Sim-Mechanics block model for 2-DOF planar robotic manipulator is shown in Figure 2. The Sim-Mechanics link of the SolidWorks model which is created using SolidWorks were imported into MATLAB to form the above shown block model and for further modelling as well. In this paper, the Sim-Mechanics block model obtained for 2-DOF planar robotic manipulator has been simulated to get results for the variations of reaction force and reaction torque acting on the robotic manipulator.

Figure 3 shows the variations of reaction force and reaction torque of joint angle θ_1 for link 1 of 2-DOF planar robotic manipulator. As can be seen from Figure 3, for the up-down movement of link 1 of 2-DOF planar robotic manipulator, the reaction force applied remains the same throughout the movement while reaction torque reduces when link 1 is moving in downward direction. Figure 4 shows the variations of reaction force and reaction torque for joint angle θ_2 of link 2 of 2-DOF planar robotic manipulator. As can be seen from Figure 4, for the up-down movement of link 2 of 2-DOF planar robotic manipulator, the reaction force applied remains the same throughout the movement while reaction torque increases when link 2 is moving in downward direction. The variations obtained for reaction force and reaction torque acting on the two links of 2-DOF planar robotic manipulator shows that the physical modelling of the robotic manipulator has been done correctly on the Sim-Mechanics software platform. The obtained variations can further be used for kinematic and dynamic analysis without involving any equations of motion.

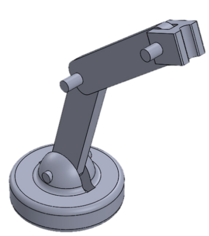

Figure 1. SolidWorks model for 2-DOF planar robotic manipulator.

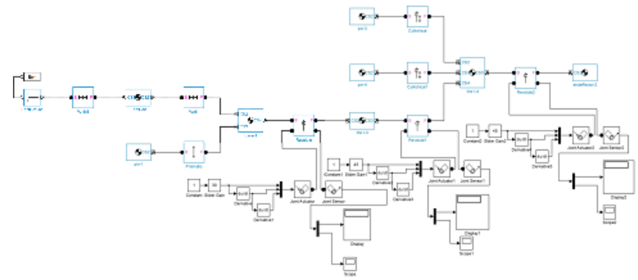

Figure 2. Sim-Mechanics block model of 2-DOF planar robotic manipulator.

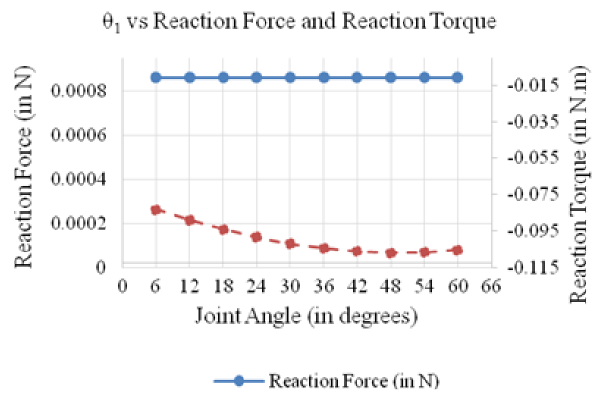

Figure 3. θ_1 vs. reaction force and reaction torque for 2-DOF planar robotic manipulator.

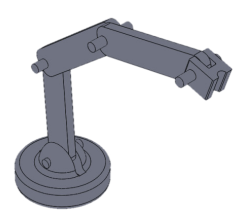

Figure 4. θ_2 vs. reaction force and reaction torque for 2-DOF planar robotic manipulator.

Table 1. Description of movement of 2-DOF planar robotic manipulator

Links	Link lengths (mm)	Range of rotation
1	$a_1 = 132$	0^o - 60^o
2	$a_2 = 132$	0^o - 90^o

1.3 Modeling of 3-DOF Planar Robotic Manipulator

Here, a 3-DOF planar robotic manipulator has been considered. The SolidWorks model for 3-DOF planar robotic manipulator is shown in Figure 5. Each component of the robotic manipulator i.e. base, links and end-effector were modeled separately and assembled in SolidWorks to get the following output. The description of movement of robotic manipulator is given in Table 2.

The Sim-Mechanics block model for 2-DOF planar robotic manipulator is shown in Figure 6. The Sim-Mechanics link of the SolidWorks model which is created using SolidWorks toolbox were imported into MATLAB to form the above shown block model and for further modelling as well. In this paper, the Sim-Mechanics block model obtained for 3-DOF planar robotic manipulator has been simulated to get results for variations of reaction force and reaction torque acting on the robotic manipulator.

In Figure 7 shows the variations of reaction force and reaction torque for joint angle θ_1 of link 1 of 3-DOF planar robotic manipulator. As can be seen from Figure 7, for the up-down movement of link 1 of 3-DOF planar robotic manipulator, the reaction force applied remains the same throughout the movement while reaction torque increases when link 1 is moving in downward direction. In Figure 8 shows the variations of reaction force and reaction torque for joint angle θ_2 for link 2 of 3-DOF planar robotic manipulator. It can be seen from Figure 8, the reaction force for link 2 remains same for 3-DOF planar robotic manipulator while reaction torque increases when link 2 is moving in downward direction. In Figure 9 shows the variations of reaction force and reaction torque for joint angle θ_3 for link 3 of 3-DOF planar robotic manipulator. It can be seen from Figure 9, the reaction force for link 3 remains same for 3-DOF planar robotic manipulator while reaction torque increases when link 3 is moving in downward direction. The variations obtained for reaction force and reaction torque acting on the two links of 3-DOF planar robotic manipulator shows that the physical modelling of the robotic manipulator has been done correctly on the Sim-Mechanics software platform. The obtained variations can further be used for kinematic and dynamic analysis without involving any equations of motion.

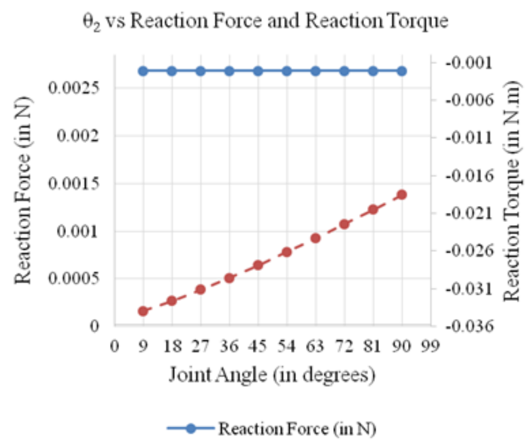

Figure 5. SolidWorks model for 3-DOF planar robotic manipulator.

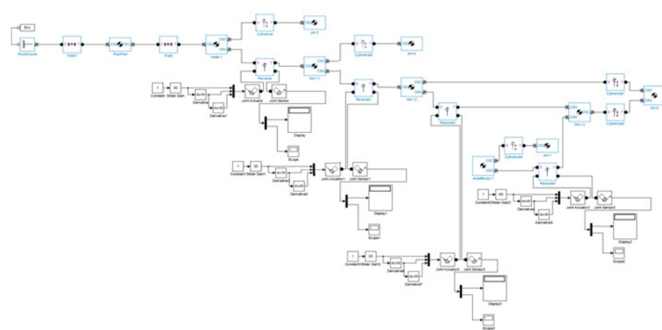

Figure 6. Sim-Mechanics block model of 3-DOF planar robotic manipulator.

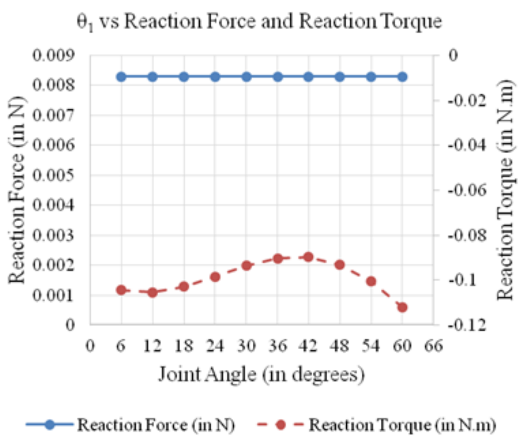

Figure 7. θ_1 vs. reaction force and reaction torque for 3-DOF planar robotic manipulator.

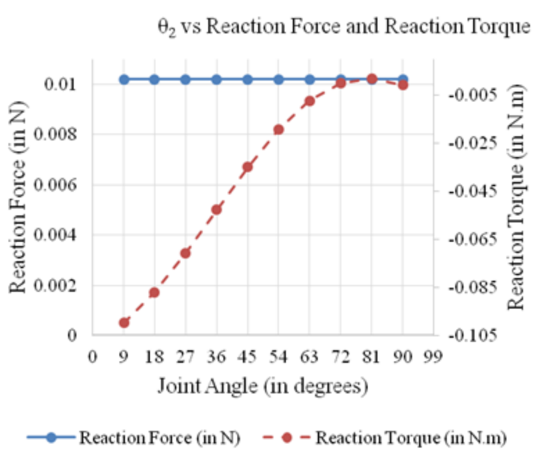

Figure 8. θ_2 vs. reaction force and reaction torque for 3-DOF planar robotic manipulator.

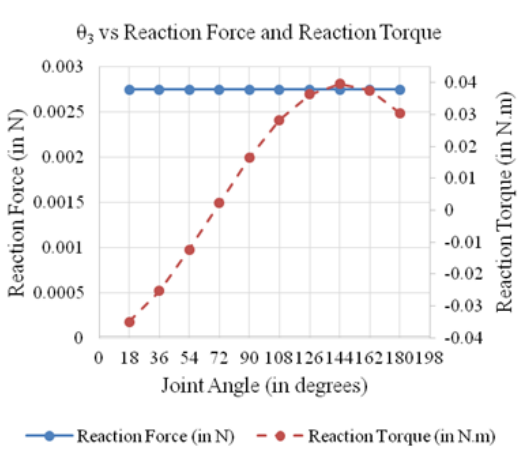

Figure 9. θ_3 vs. reaction force and reaction torque for 3-DOF planar robotic manipulator.

Table 2. Description of movement of 3-DOF planar robotic manipulator

Links	Link lengths (mm)	Range of rotation
1	$a_1 = 132$	0° - 60°
2	$a_2 = 132$	0° - 90°
3	$a_3 = 132$	0° - 180°

2. Conclusions and Future Scope of the Work

This paper presents Sim-Mechanics software as an important tool for modelling multi-DOF robotic manipulators without any mathematical equations or relations. To ease the complexities of dynamic modelling, SolidWorks software has been used to model the rigid bodies and then the model has been imported on the Sim-Mechanics software platform. This helps in avoiding the analytical calculations and gives a better visualization of the model. The Sim-Mechanics block model has been used to obtain the results for variations of reaction force and reaction torque acting on the robotic manipulator, which thereby validates the proper development of the model. In future, more complex architectures of multi-DOF robotic manipulators can be modelled using the Sim-Mechanics software. Further analysis related to forward dynamics, inverse dynamics, trajectory planning etc. will be attempted.

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