Dynamic Simulation of a 4 Degree of Freedom (4DOF) Robotic Arm for Small and Medium Scale Industry Packaging.

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ABSTRACT

This work presents a report on development and examination of the behavior and performance of a 4 degree of freedom (DOF) robotic arm by simulation through Autodesk Inventor. This robotic arm is meant for a small and medium scale packaging operation. A 3D model of the manipulator was built; with a total reach of 840mm to carry a maximum payload of 1kg. Dynamic simulations were carried out on the model to examine properties such as torque variation at the joints, speed, and trajectory of the manipulator.
Analysis such as collision detection to maximize displacement of links, motion load and stress analysis to examine stress distribution in links were also carried out. The simulations carried out showed that the manipulator has expected responses similar to a physical model. Maximum velocity of end effector is 0.23m/s and acceleration of 0.11m/s^2. The robotic arm has a total mass of 8.7kg. This simulation method will help to reduce the need for testing on physical systems as long as the model sufficiently represents robotic arm to be built.

(*Keywords:* dynamic simulation, virtual prototype, robotic arm, Autodesk Inventor, 3D modeling)

INTRODUCTION

A robotic arm is a complex system in which there are coupling relationships between nonlinear features. This relationship includes mechanical connections and control systems to achieve the performance of the system (Haitao *et al.,* 2013).

The traditional method of design has been to design a physical model and carry out experiments and analysis on it to evaluate its performance in a continuous iterative process.
This method usually takes plenty of time and incurs huge cost, and sometimes does not result in an optimum design (Robinson, 1996).

As quoted by Haitao *et al.* (2013), Gu et al. (2005) stated that if virtual prototypes are built first before real models, kinematic and dynamic simulation analysis can be carried out on a robotic arm to improve the whole mechanical system and control system. So simulation can help shorten development cycle and help to achieve quick improvement and efficiency. Jambak (2010) also stated that simulation covers the visualization of how the robot moves through its environment, relying heavily on CAD and graphical visualization tools, and also on numerical calculations which deals with the dynamics, sensing and control of the robots.

Autodesk Inventor is a comprehensive modeling system that allows complex assemblies to be created from individual part models during the design process. It has great advantage in that its assembly modeling process allows the design team to ensure that all parts fit together and function as intended. Also, as a result of this process, the mechanical properties of the individual parts and the overall assembly are available to use for simulation. Dynamic Simulation in Inventor provides a tool for computing the dynamic motion and associated constraint forces in mechanical assemblies, and is associative, that is part and constraint information is automatically updated when changes are made to the assembly.

Simulation has been applied by many researchers in many ways to robotic arms. Haitao et al. (2013) used MATLAB/SIMULINK to study how to quickly establish the virtual prototyping model of robot arm system and effectively solve trajectory tracking control for a given signal. Duicu and Popa (2012) presented the Modeling and simulation of a 5-axis robot arm trajectory using SolidWorks for the modeling and MATLAB/SIMULINK for the trajectory simulation.

Mellardo et al. (2003) introduced VirtualRobot: An open general-purpose simulation tool, a graphical software application, designed for low cost hardware, as a general, flexible and open platform to work on Robotics. Ferretti *et al*. (2008) also presented the DEXARM Real-Time Simulation (DRTS) tool conceived to support the design and development of the controller of the Dexterous Robot Arm(DEXARM), a lightweight 7 DOFpace robotic arm.

In this study, we present the dynamic simulation of a 4 DOF robotic arm for small and medium scale industry packaging using Autodesk Inventor. This work is carried out to enable us have a better understanding of the attributes and performance of the robotic arm prior to physically building and fabricating the system. This will help to reduce cost and minimize errors in the physical development of the robotic arm.

Most dynamic simulation of robotic arms include the use of two or more software, while we have presented the use of Autodesk Inventor (with student, non-commercial license) as a software capable of covering major areas of robotic arm simulation such as the 3D modeling, joint torque simulation, trajectory tracking, motion load analysis and collision detection. This is a part of an on-going work on the development of the robotic arm. At this stage we aim to define spatial and kinematic relationship between links of the robotic arm, simulate motion between components, check for collision, analyze range of motion of entire system and visualize system performance. This will enable us to iteratively improve the design to achieve an optimum system.

MATERIALS AND METHODS

Our robotic arm is designed to be able to work from a raised platform or a table top. It has an arm reach of 840mm to carry a payload of 1kg. The reach of the robotic arm is similar to that of an adult human arm. The mechanical design has been limited to 4 DOF because such a design allows most of the necessary movements in robotic arm, and help to reduce cost and complexity (Elfasakhany et al, 2011). Figures 1 and 2 show the schematic of the robotic arm.

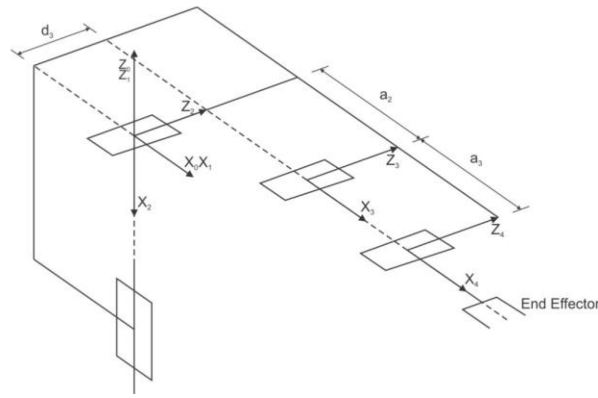

Figure 1: Schematic of the Robotic Arm showing Fame Assignment, Links and Joints.

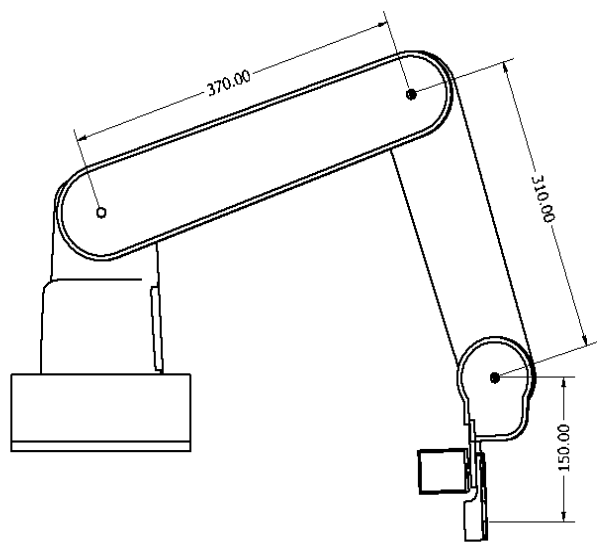

Figure 2: Schematic of the Robotic Arm showing Link Lengths.

Torque Calculation

To verify our simulations, we need to obtain by calculation the torque at each joint so as to compare with the result of the simulation. The torque for each joint was calculated by multiplying the force acting on link by the distance between the force and the joint. Figure 3 shows a schematic of the forces acting on the robot arm and Equations 1 to 3 are used to calculate the respective joint torques.

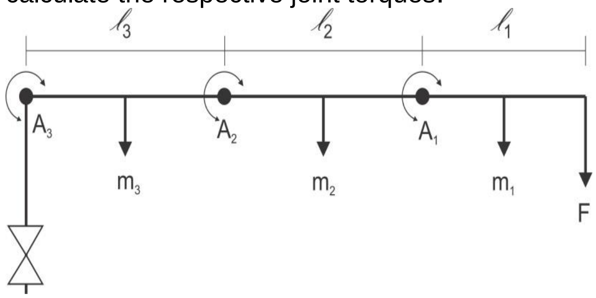

Figure 3: Joint Torque Parameters.

Joint Torques :

$$\tau_1 = m_1 \times \frac{1}{2} l_1 + F l_1 , \quad (1)$$

$$\tau_2 = m_2 \times \frac{1}{2} l_2 + A_1 \times l_2 + m_1 \left(l_2 + \frac{1}{2} l_1 \right) + F(l_2 + l_1) \quad (2)$$

$$\tau_3 = m_3 \times \frac{1}{2} l_3 + A_2 \times l_3 + m_2 \left(l_3 + \frac{1}{2} l_2 \right) + A_1(l_3 + l_2) + m_1 \left(l_3 + l_2 + \frac{1}{2} l_1 \right) + F(l_3 + l_2 + l_1) \quad (3)$$

Where;
$m_{1,2,3}$= Weight of links
$l_{1,2,3}$ = Length of links
$A_{1,2,3}$ = Weight of actuators
F = Weight at the end of wrist (weight of end effector and payload)

These design considerations were used to build a virtual prototype of the robotic arm in Autodesk Inventor professional 2013; Figures 4 to 9 show views and parts of the robotic arm in Autodesk Inventor professional 2013. The total mass of the robotic arm is 8.7kg.

To simulate the robotic arm, the Autodesk inventor dynamic simulation environment was used. The displacement of the robotic arm joints was simulated at constant velocity, attaching the maximum payload of 1kg and weight of the end effector at the wrist, to examine the dynamic properties of the robotic arm. Results are shown in Figures 11 to 16.

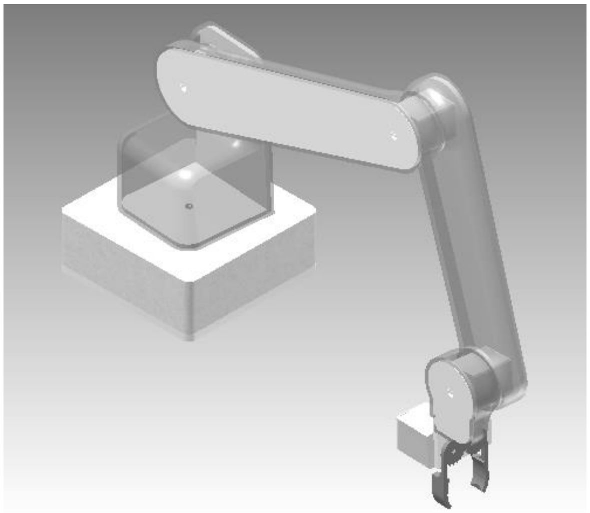

Figure 4: CAD Model of the 4 DOF Robotic Arm.

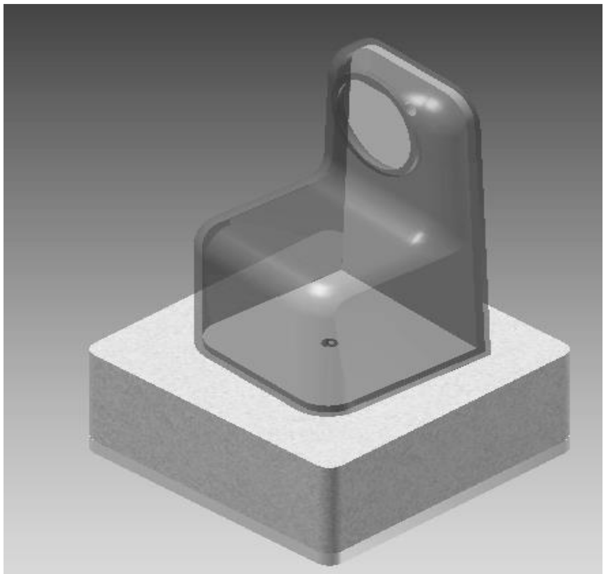

Figure 5: Model of Robot Arm Base and Shoulder.

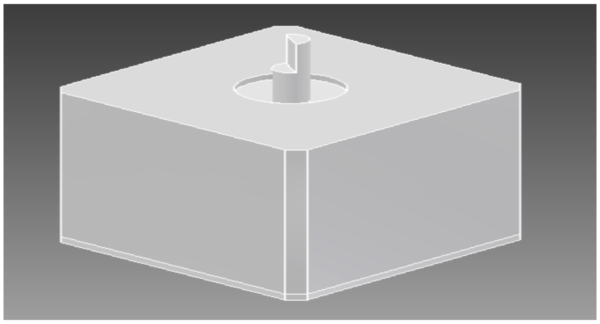

Figure 6: Model of Stepper Motor.

Figure 7: Model of Robot Arm Lower Arm and Cover.

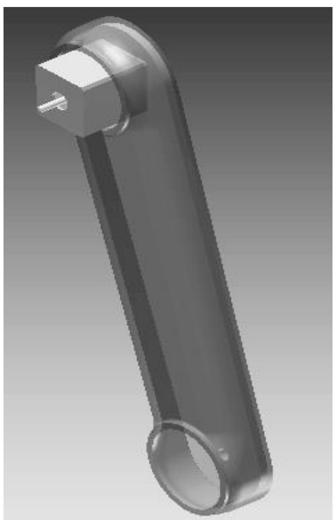

Figure 8: Model of Robot Arm's Upper Arm, Cover and Stepper Motor.

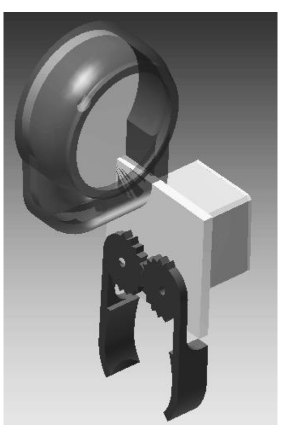

Figure 9: Model of Robot Arm Gripper Assembly and Cover.

RESULTS AND DISCUSSION

Dynamic simulation of the robotic arm was carried out to analyse velocity, acceleration and the torque variation of the joints on the robotic arm. It is importance to know the torques needed at the joints that will drive the robotic arm. The simulation therefore gives us the variation of the joint torques with time at constant joint velocities; results are shown in Figure 10 and Table 1. This will assist in the selection of appropriate actuators for the fabrication of the robotic arm. Figure 11 also shows the variation of the velocity and acceleration of the end effector with time. Maximum velocity and acceleration of the end effector is 0.23m/s and 0.11m/s respectively.

The simulation was also used to track the trajectory of the wrist as the robotic arm stretches out from the home position to the maximum reach (Figure 10). This is useful in motion planning of the robotic arm; enabling us to see the path of the end effector when the robotic arm is being manipulated.

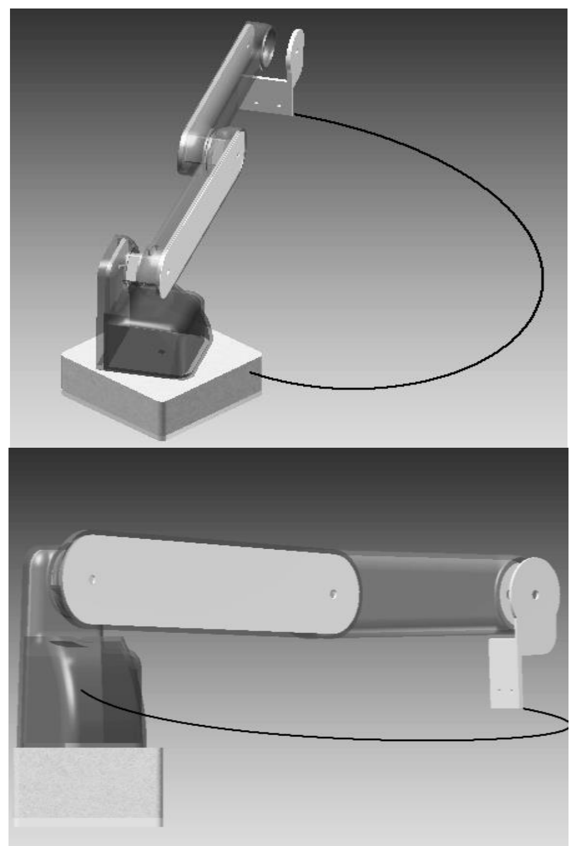

Figure 10: Trajectory Tracking of Robotic Arm Stretching out to the Maximum Reach.

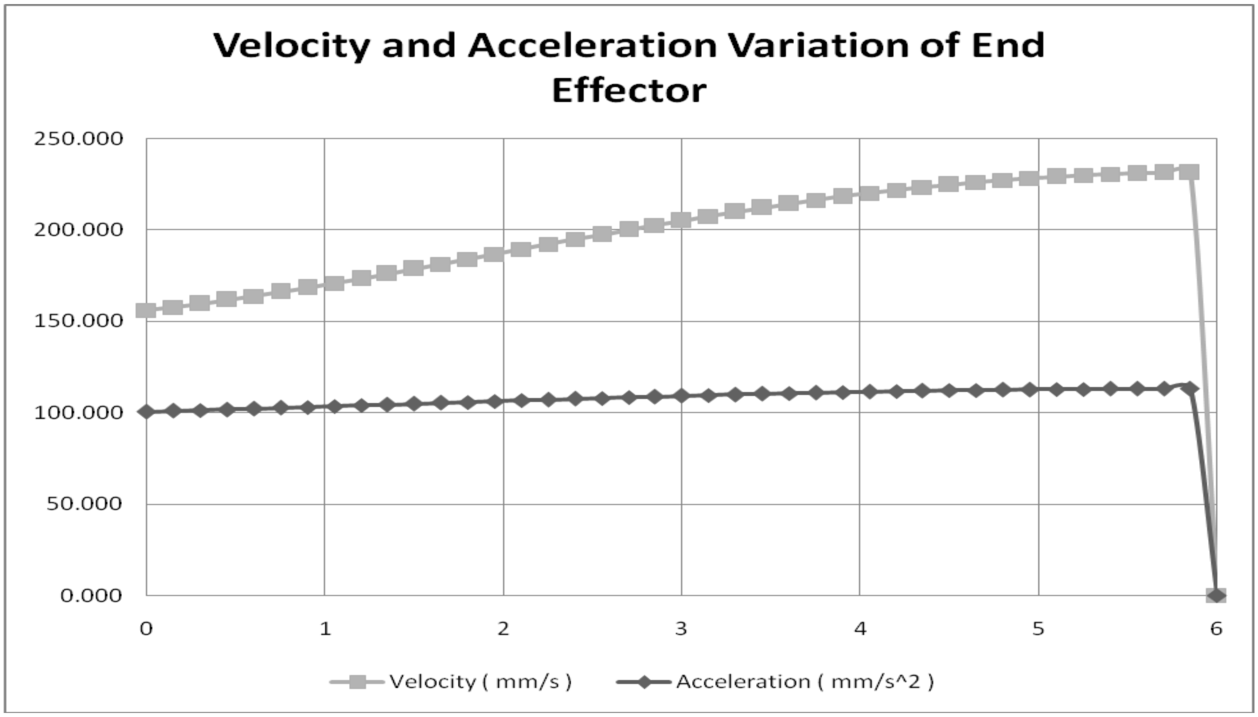

Figure 11: Variation of Velocity and Acceleration with Time during Simulation.

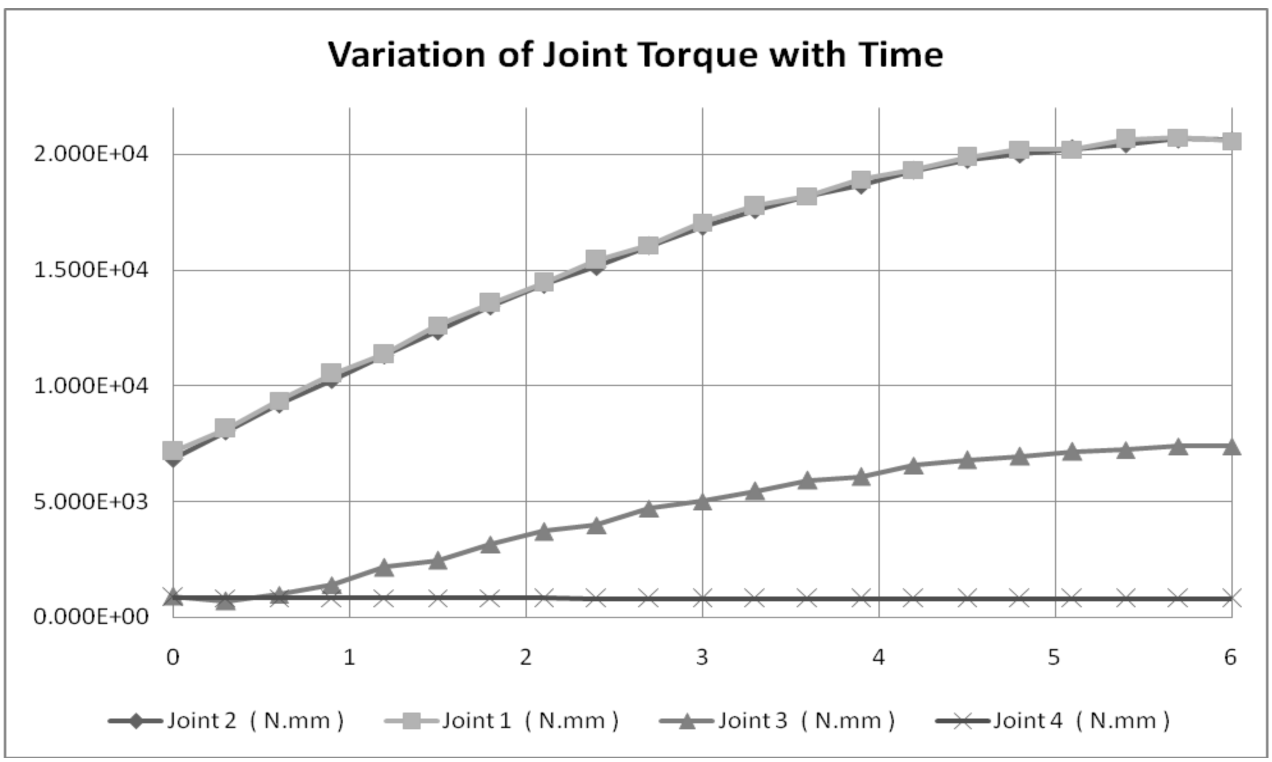

Figure 12: Variation of Joint Torques with Time during Simulation.

Collision Detection

Autodesk Inventor has a contact solver module in the assembly environment which does real time collision detection in model simulations. This module was used to determine areas of collision in the model, and therefore improved the design to allow maximum displacement in the joints. Table 1 also shows the range of displacement at the joints during the simulation.

Motion Load Analysis

With Autodesk inventor, stress analysis of the robotic arm was carried out when subjected to simulated dynamic conditions. Here, we investigated the motion load analysis in the links when the torques at the joints is at the maximum. This will help to see if the material chosen can fail at this condition. Figures 13 to 16 show the result of the motion load analysis on the links of the robotic arm.

The results presented shows that the robotic arm is capable and rigid enough to carry the maximum payload. The maximum Von Misses stress was seen in the shoulder which is equal to 98.2 MPa, at a very minute position. This value is below the ultimate yield stress for Aluminum 6061 which is 125 MPa. Also the maximum displacement in the robotic arm was seen to be 0.2653mm which is also on the shoulder. This displacement is also within acceptable range.

Table 1: Joint Simulation Result.

Joint	Max Joint displacement (deg)	Displacement (deg)	Velocity (deg/sec)	Max. Dynamic Torque (N.mm)	Calculated Static Torque (N.mm)
1	360	120	20	21093	-
2	218	60	10	20612	13664.34
3	328	150	25	7549	8316.82
4	250	90	15	1105	1532.13

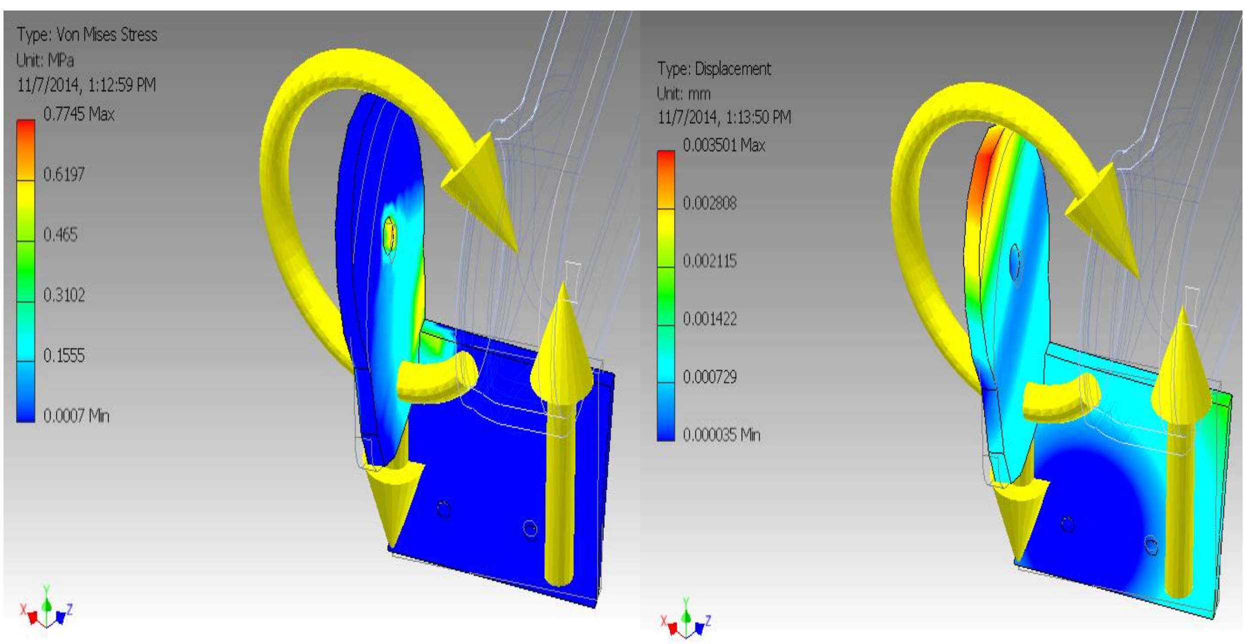

Figure 13: Motion Load Analysis on Wrist showing Von Mises Stress and Displacement.

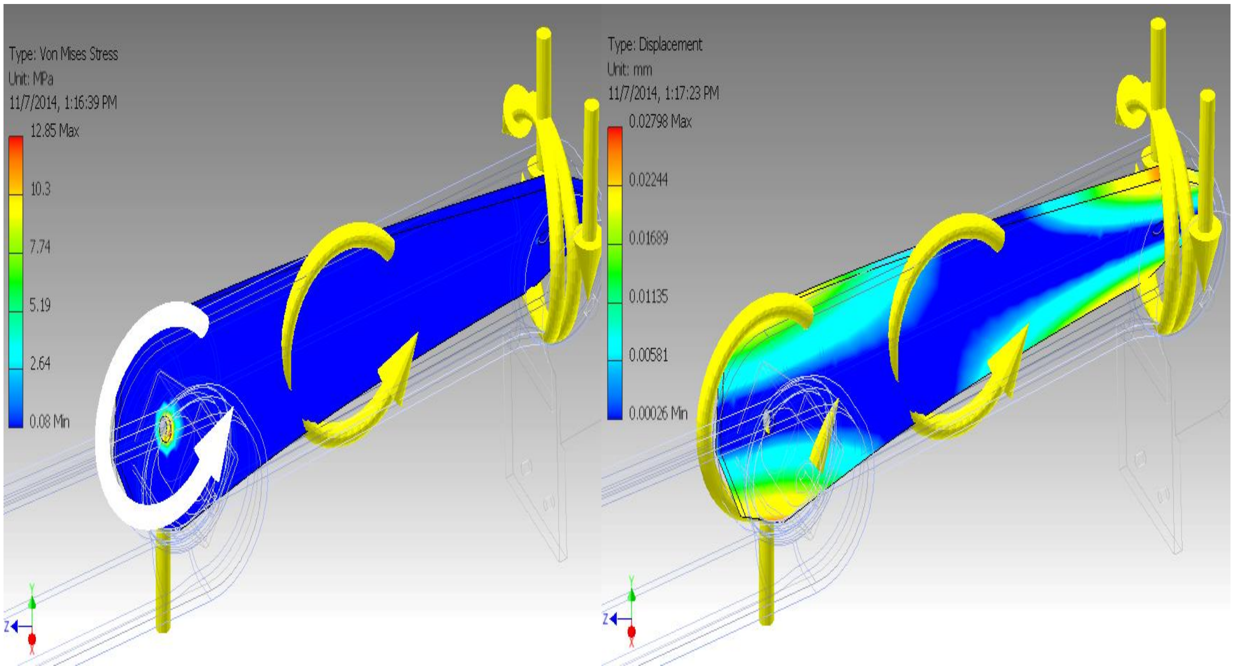

Figure 14: Motion Load Analysis on Upper Arm showing Von Mises Stress and Displacement.

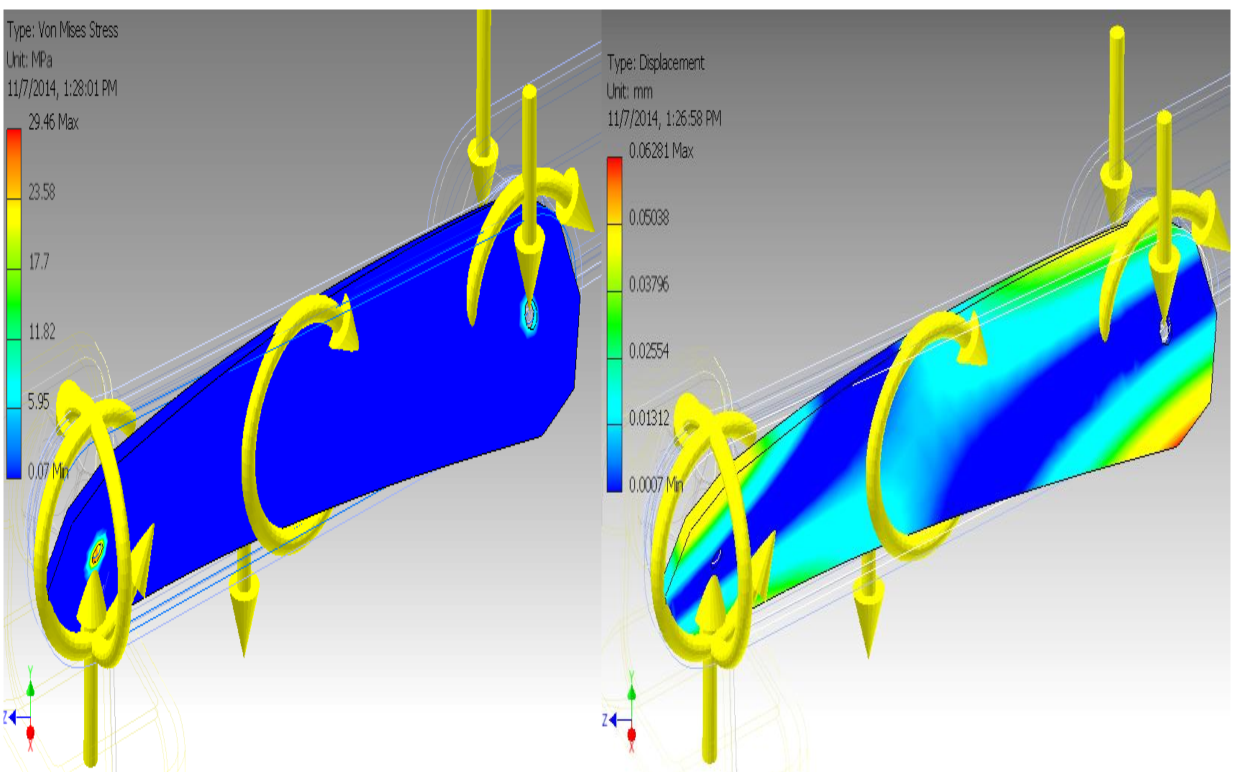

Figure 15: Motion Load Analysis on Lower Arm showing Von Mises Stress and Displacement.

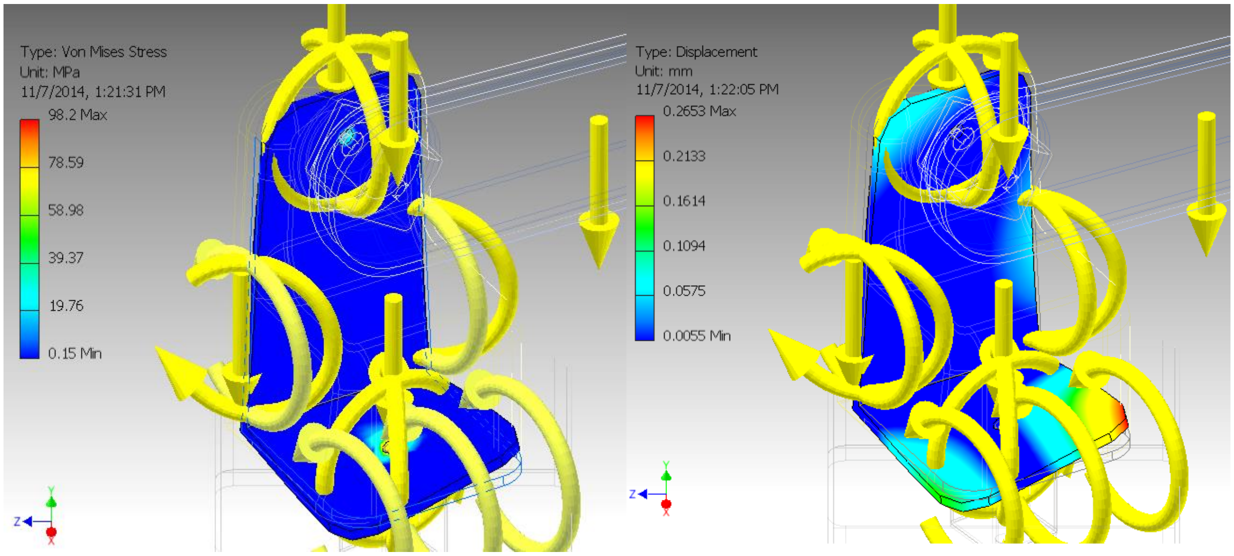

Figure 16: Motion Load Analysis on Shoulder showing Von Mises Stress and Displacement.

CONCLUSION

The dynamic simulation of a 4 DOF robotic arm for small and medium scale industry packaging has been presented with all necessary details. The simulation was used to analyze the torque variation at the joints, the motion loads and stresses on the links of the robotic arm. Collision detection analysis was also used to find and maximize the maximum displacements of the links. Simulation results indicate that the robot arm system has preferable response characteristics, and is capable of carrying the proposed payload. Therefore, the simulation method we have presented will help to reduce cost and minimize errors in the physical development of the robotic arms.

It is also a cost effective solution because only one software is employed in the simulation process, and it is more or less free as long as the purpose is for research and education. However, we have not considered inverse kinematics simulation and trajectory planning as they may be beyond the scope of Autodesk Inventor, but this can be achieved by interfacing with a 3rd party program like MATLAB/SIMULINK.

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