Multibody Dynamic Analysis of a Gantry Robot for Automatic Egg Transferring Process Using RecurDYN

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ARTICLE INFO

Article history:
Received: 26 May 2023
Revised: 23 July 2023
Accepted: 22 August 2023

Keywords:
Multibody dynamic Simulation
RecurDYN
Euler-Lagrange Method
Gantry Robot
Automation

ABSTRACT

In this paper, we present a method for modeling and dynamic simulation of a gantry robot using the software RecurDYN. Automation in manufacturing can bring many benefits to small and medium-sized enterprises (SMEs), including increased productivity, reduced reliance on skilled labor, cost savings, and higher revenue. The use of simulation and analysis prior to machine building is crucial for small-scale manufacturing enterprises. By using SOLIDWORKS, the 3D model of the robot was being created in this study. The resulting model was then imported into the multibody dynamic simulation environment of RecurDYN in Parasolid file format. By applying the mass of components and a pre-defined trajectory of certain coasting velocity based on a trapezoidal motion profile and an S-curved motion profile as boundary conditions, the multibody dynamic simulation was performed. Robot based on the Euler-Lagrange method, comparison with theoretical dynamic analysis of the robot was being verified by the reliability of the simulation. The results of this verified simulation study can be utilized in the physical machine building and motion system design.

1. INTRODUCTION

In hatchery farms, eggs can be manually transferred by placing a hatcher basket upside down over an egg tray and then flipping them both over together. Alternatively, a specialized framework can be used to perform the transfer. However, this method has several drawbacks. In addition to increasing the number of cracks in the eggs, manual transfer often fails to remove clear eggs, resulting in many inverted eggs. This causes the egg fluid to transfer to the air cell at the bottom, leading to late mortality of the chicks. If the chicks do hatch, they often appear scruffy and are consequently culled[1].

A hatching egg cart length is1660mm, width is 570mm and the height is 2100mm. The 30 eggs are being carried in an egg cart and 150 egg carts are being placed in each egg tray. The men-powered loading and discharge of the egg tray is hard and inefficiency because if the inconvenient of the truck limitation and the diameter of the egg tray [2].

Therefore, the automatic carried the eggs from the tray transferred into the hatcher basket need to be done smoothly in a few steps with possible maximum capacity and minimizing the risk of cracks.

The gantry robot, a type of Cartesian robot, is a widely utilized and versatile automation system in various industrial applications. Its working principle revolves around a rectangular Cartesian coordinate system, wherein three linear axes (X, Y, and Z) are employed for movement along their respective directions. The gantry robot typically consists of a fixed base and a moving gantry structure that carries the tool or payload. Precision lead screws, belts, or linear motors actuate each axis, ensuring accurate and repeatable positioning of the end effector. To accomplish complex tasks, the control system drives each axis independently or synchronously, enabling seamless motion along the X, Y, and Z axes. Its inherent stiffness and high load-carrying capacity make the gantry robot an excellent choice for handling heavy objects or performing tasks that require superior precision. As manufacturing demands continue to evolve, the gantry robot's adaptability and efficiency position it as a prominent solution for enhancing productivity and streamlining automation processes across various industries. The gantry robot system tooling with vacuum suction unit is a convenient design for picking and placing the eggs. The system can be design in a 3D modeling and its dynamic behavior can be analyzed with a multibody dynamic analysis software beforehand based on certain environmental conditions. The simulation results can be verified by comparing the results of the theoretical dynamic calculation with the same input parameters. The data from the verified simulation models such as torques exert at the revolute joints of the motors can be used to design the motion control system.

In this study, the system is designed in SOLIDWORKS and multibody analysis simulation is performed with

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RecurDYN based on motion profile and masses of components.

2. STRUCTURE DESIGN OF GANTRY ROBOT FOR AUTOMATIC EGG TRANSFERRING PROCESS

The structure design and the coordinate system of the gantry robot are shown in Figure 1. and the gravity is in downward direction. m_1, m_2 and m_3 are the groups of moving masses of the system. d_1, d_2 and d_3 describe linear displacements in X-axis, Y-axis and Z-axis direction respectively. The X-axis has two stepper motors to drive the movement of the moving masses $(m_1 + m_2 + m_3)$. The Y-axis is driven by one stepper motor and it moves $(m_2 + m_3)$. The Z-axis has one pneumatic cylinder for picking up the eggs with the vacuum suction unit (m_3) from the tray and putting down into the hatcher basket.

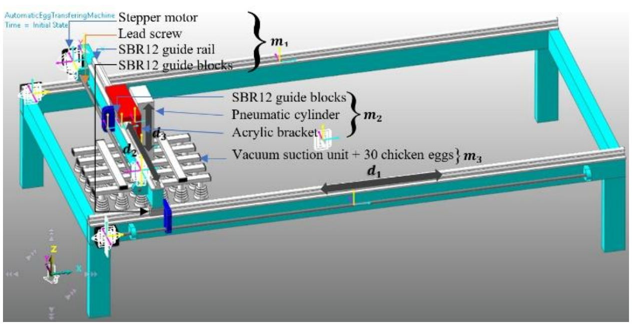


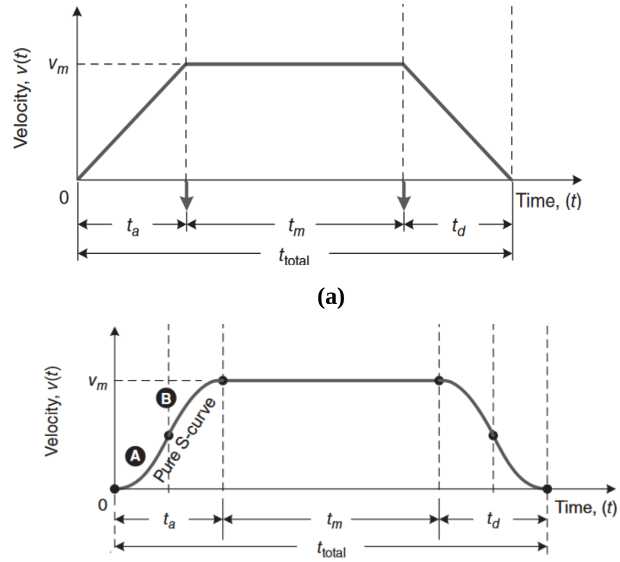
Fig. 1. The structural design and the coordinate system of gantry robot.

3. BACKGROUND THEORIES OF DYNAMIC ANALYSIS OF GANTRY ROBOT

3.1. Trajectory Planning

The generation of a trajectory connecting two points, "A" and "B," is necessary at the time that an axis of a device needs to shift between these points. In the field of motion control, this trajectory is referred to as a motion profile and should be facilitated smoothly speed up of the axis from point "A" to a constant operational velocity, sustained movement at this velocity for a period of time, and a smooth deceleration to a halt at point "B." To achieve this, a motion controller creates the moving profile at steady intervals, and subsequently produces velocity and position commands for the servo processing structure of each equipment. These commands are then utilized by the servo control system to regulate the motor signals and guide the axis along the desired motion profile[3].

Motion profiles are used in dynamic analysis to understand the response of a system or structure to changes in velocity. This is important because the velocity of a system can have a significant effect on its behavior, and an accurate velocity profile can help predict how the system will respond to different conditions.



(b)

Fig. 2. (a) Trapezoidal velocity profile, (b) S-curve velocity profile [3]**.**

Additionally, an accurate velocity profile can help predict how the system will respond to different conditions.

There are two commonly used motion profiles:

- Trapezoidal velocity profile and
- S-curve velocity profile[3], [4].

3.1.1. Trapezoidal Velocity Profile

The trapezoidal velocity profile is well-known due to its simplicity.

There are three unmistakable point in this profile:

(1) acceleration,

(2) steady speed (zero acceleration), and

(3) deceleration [5].

To shift along an axis of the equipment, normally the following required movement parameters are known:

- Move velocity V_m
- Acceleration a
- Distance s.

To calculate the move time t_m which is the time frame of moving with move velocity V_m, we can apply the geometric direction to Figure 2(a) beginning with the incline of the velocity curve $a = \frac{v_m}{t_a}$.

$$t_a = t_d = \frac{v_m}{a} \tag{1}$$

where, the acceleration time t_a and the deceleration time t_d are assumed to be equal. Total distance L traveled along the axis can be done by inserting the spaces of the two triangles and the rectangle by the velocity loop, $t_a = t_d$:

$$L = \frac{t_a v_m}{2} + t_m v_m + \frac{t_d v_m}{2} = v_m(t_a + t_m) \tag{2}$$

The time movement can be initiated as

$$t_m = \frac{L}{v_m} - t_a \quad (3)$$

$$a = \frac{v_m}{t_a} \quad (4)$$

The motion profile can be generated by applying the movement speed and the time and used to program the motion controller to travel distance L [3].

3.1.2. S-curve Velocity Profile

The trapezoidal velocity profile, a widely-used motion control pattern known for its computational simplicity, has a remarkable disadvantage. The sharp corners in its shape occur abrupt acceleration changes, leading to infinite jerks within the system. To mitigate this problem and achieve smoother acceleration, these corners are rounded, emerging in the S-curve velocity profile depicted in Figure 2(b). The curved shape of the S-curve profile, adjusted using second-order polynomials [6], smoothing the arrangements between plus, zero, and minus acceleration development. Different from the trapezoidal counterpart, the S-curve profile has variable acceleration and finite jerk. This is essential for maintaining uninterrupted operation during sudden loads, crucial in fields like robotics and CNC machinery that demand precision and fluidity [6]. In essence, the S-curve velocity profile refines the trapezoidal version by resolving infinite jerk issues. Through corner rounding, the S-curve ensures seamless acceleration shifts, enabling controlled, continuous movement – a critical requirement in precision-focused domains like robotics and CNC machinery [4], [7].
Implementing an S-curve motion profile in control systems effectively eliminates sudden changes in force, torque, and motor current demands. This diminishes high-frequency oscillations that can harm motor longevity and system accuracy. The S-curve profile enhances motor performance, lifespan, and motion control precision [8].

The aggregate interval movement by the axis and the move timet_m can be calculated by the equation 2&3 respectively.

The acceleration time can be calculated by

$$t_a = t_d = \frac{2v_m}{a} \quad (5)$$

The calculation of the loop A in Figure 2(b) is

$$v_A(t) = \frac{a^2}{2v_m}t^2 \quad (6)$$

The calculation of the loop B in Figure 2(b) is

$$v_B(t) = v_m - \frac{a^2}{2v_m}(t_a - t)^2 \quad (7)$$

By differentiating Equation (6) and (7), the acceleration equations for curve A and B respectively are

$$a_A(t) = \frac{a^2 t}{v_m} \quad (8)$$

$$a_B(t) = \frac{a^2(t_a - t)}{v_m} \quad (9)$$

3.2. Dynamic Model of Gantry Robot

The dynamic model of a robot behavior is reacting to internal and external incentive is narrated by its mathematical representation of the system. For Cartesian control outline and the creation of high-quality controllers, basic physical laws can be attained and understood the powerful behavior and the robot through a mathematical model[9], [10].

There are two commonly used approaches to designing dynamic models of robots: the Euler-Lagrange method and the Newton-Euler method. One of the most widely used method is the Lagrange's equations of motion, which is accordant with the two generalized calculations for linear and rotational movements[11]–[13].

3.2.1. Lagrange's Equations of Motion

The determination of the dynamic relationships governing the motions of a robot is crucial in determining the strength required for each actuator. The force-mass-acceleration and torque-inertia-angular-acceleration equations are considered as the external loads on the robot. By analyzing these loads, the designer can calculate the maximum loads that the actuators may be subjected to and design the actuators accordingly to deliver the necessary forces and torques[12].

Lagrangian mechanics is according to the two universal calculations: one for linear movement and one for the rotational movement. Firstly, we construe a Lagrangian as:

$$L = K - P \quad (10)$$

where, L is the Lagrangian, K is the kinetic energy of the system, and P is the potential energy of the system [12].

The function L, the difference of the kinetic and potential energy, is called the Lagrangian of the system, and Equation (10) is known as the Euler-Lagrange Equation. The Euler-Lagrange equations offer a framework for expressing the dynamic equations of motion that are equivalent to the ones obtained through Newton's Second Law[14].

$$F_i = \frac{\partial}{\partial t}\left(\frac{\partial L}{\partial \dot{d_i}}\right) - \frac{\partial L}{\partial d_i} \quad (11)$$

where F_i is the summation of all external forces and d_i is system variables.

$$L = K - P = k_1 + k_2 + k_3 - p_1 - p_2 - p_3$$

$$= \frac{1}{2}(m_1 + m_2 + m_3)\dot{d}_1^2 + \frac{1}{2}(m_2 + m_3)\dot{d}_2^2 + \frac{1}{2}m_3\dot{d}_3^2 - m_3 g d_3 \quad (12)$$

Where k_1, k_2, k_3 and p_1, p_2, p_3 are the kinetic energies and the potential energies of the three mass groups (m_1, m_2, m_3) respectively. $\dot{d}_1, \dot{d}_2\ and\ \dot{d}_3$ are the linear velocities along X, Y and Z direction, respectively.

$$F_1 = (m_1 + m_2 + m_3)\ddot{d}_1 \quad (13)$$

$$F_2 = (m_2 + m_3)\ddot{d}_2 \quad (14)$$

$$F_3 = m_3\ddot{d_3} + m_3 g \tag{15}$$

F_1, F_2 and F_3 are the forces of actuators at joints for X, Y and Z axis individually. The dynamical formula is easy to determine. The first phrase in each formula is speed up, while the second term is centripetal term (same to zero). The third phrase in the formula (15) is gravity section and the equation is same to zero in equation (13) and (14)[15].

By using vector, we can compose the related dynamic formula of the gantry device as present following equations:

$$\begin{bmatrix} F_1 \\ F_2 \\ F_3 \end{bmatrix} = \begin{bmatrix} m_1 + m_2 + m_3 & 0 & 0 \\ 0 & m_2 + m_3 & 0 \\ 0 & 0 & m_3 \end{bmatrix} \begin{bmatrix} \ddot{d_1} \\ \ddot{d_2} \\ \ddot{d_3} \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ m_3 \end{bmatrix} g \tag{16}$$

4. MULTIBODY DYNAMIC ANALYSIS WITH RecurDYN

Multibody dynamics (MBD) covers a system of many bodies linked together via kinematic constraints[16]. Multibody dynamic analysis with RecurDYN is a method of analyzing the dynamic behavior of systems with multiple interconnected components. It is used to predict the motion and forces in the system under different operating conditions, such as different speeds, loads, and boundary conditions.

Table 1. Masses of components of m_1

Name	Mass
Stepper motor	0.35 kg
8mm lead screw of 1m length	0.3 kg
2 SBR12 linear guide rails of 1 m length	1.2 x 2 = 2.4 kg
4 SBR12UU guide blocks	0.065 x 4 = 0.26 kg
Bracket made from acrylic sheet	0.5 kg
Hollow square pipe	3.62 kg
Total	10.13 kg

Table 2. Masses of components of m_2

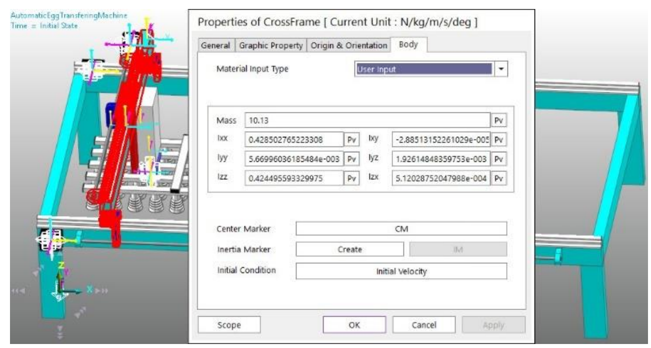
Name	Mass
Pneumatic cylinder	0.5 kg
4 SBR12UU guide blocks	0.065 x 4 = 0.26 kg
Bracket made from acrylic sheet	0.5 kg
Total	1.26 kg

Table 3. Masses of components of m_3.

Name	Mass
30 chicken eggs	70 x 30 = 2.1 kg
Vacuum suction unit	0.7 kg
Total	2.8 kg

4.1. Modeling of the simulation system

The 3D model of the gantry robot is designed in SOLIDWORKS. The model is saved as Parasolid file format and imported into the simulation environment of the RecurDYN. After that the joints of the system are defined and the masses and the accelerations are assigned as the input data.



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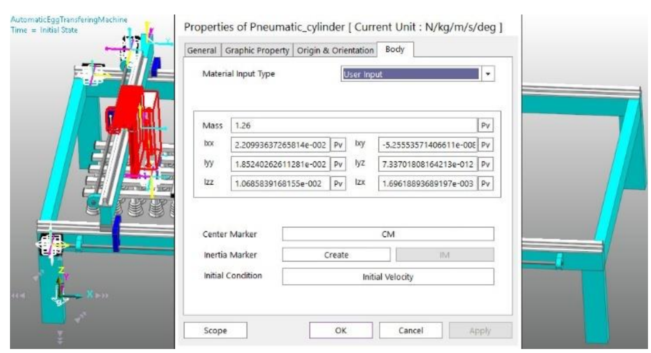

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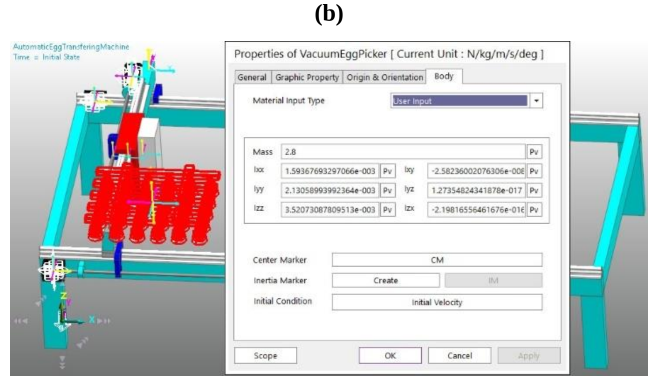


(c)

Fig. 3. The masses of group of components as boundary condition (a) m_1, (b) m_2 and (c) m_3.

4.1.1. Masses of basic components

The components are organized in three groups, m_1, m_2 and m_3. When the X-axis motor drives, the components of m_1, m_2, m_3 would move in the X direction. When the Y-axis motor drives, the components of m_2 and m_3 would move in the Y direction.

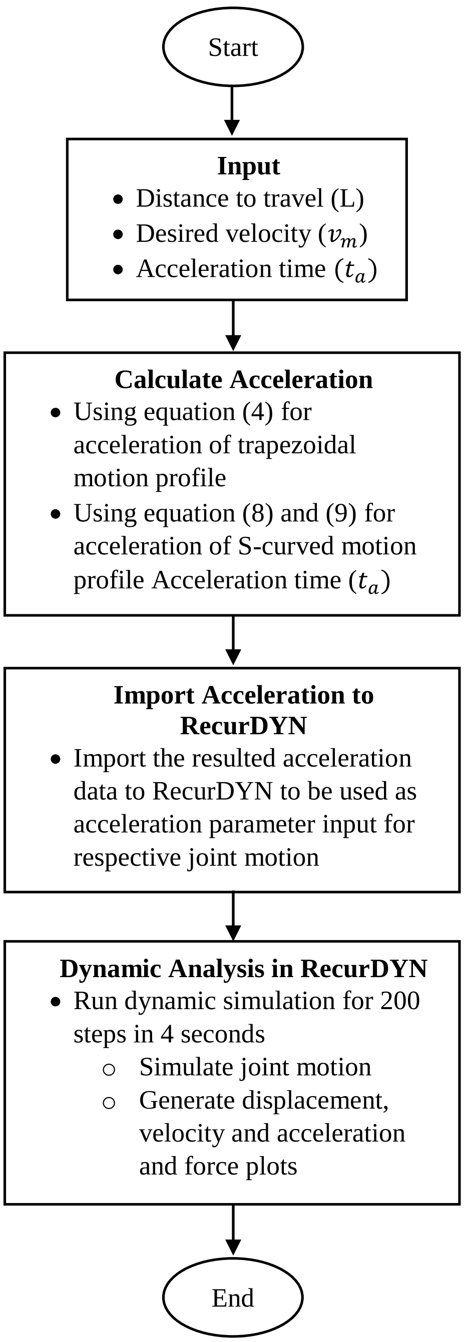


Fig. 4. The flowchart of calculating acceleration profile and setting as motion parameter in multibody dynamic analysis simulation in RecurDYN.

And the components of m_3 move in the Z direction when the pneumatic cylinder drives. The masses of components of the three groups (m_1, m_2, m_3) are described in table 1, table 2 and table 3 respectively.

4.1.2. Motion parameters

After assigning the masses of the components, the motion parameters for the joints are defined.

The motion parameters for the joints are calculated according to the motion profile equations as described above for trapezoidal and S-curved profiles based on the predefined travelling distances and times.

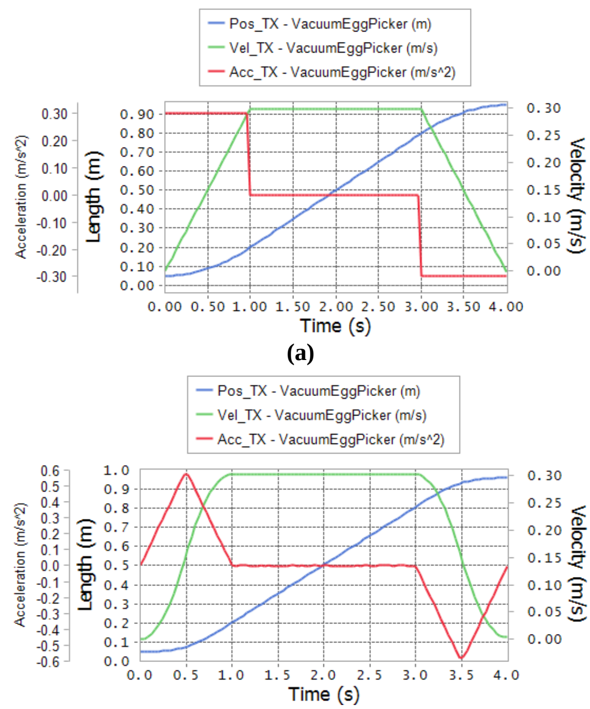
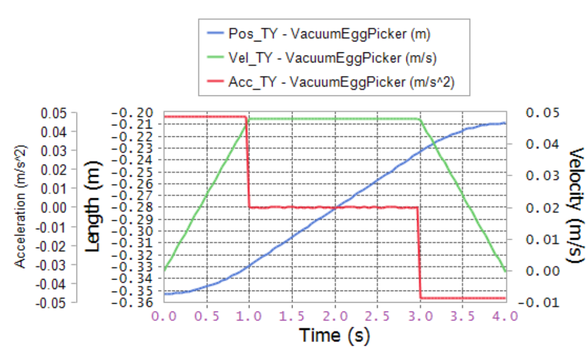
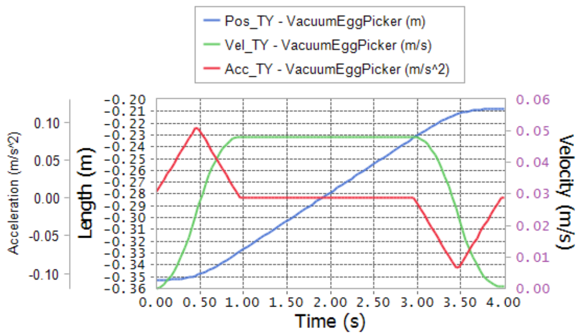


Fig. 5. The motion parameters of X-axis (a) Trapezoidal velocity profile, (b) S-curve velocity profile.

The figure 5 in above shown as; the X-axis is the longest and it has to carry all the moving masses of the system. The travelling distance is 0.9 m and the travelling time is 4 s, the same as simulation time. The coasting velocity is 0.3 ms^{-1} and it is assumed fast enough to carry the fragile eggs.



(a)



(b)

Fig. 6. The motion parameters of Y-axis (a) Trapezoidal velocity profile, (b) S-curve velocity profile.

The figure 6 is said that the motion of the axes (especially X-axis and Y-axis) are adapted so that they all begin and end at the same period (interpolated motion)[3].

Therefore, the movement contour for Y-axis is measured according to the travelling time of X-axis motion. The coasting velocity along Y-axis is 0.04 ms^{-1}.

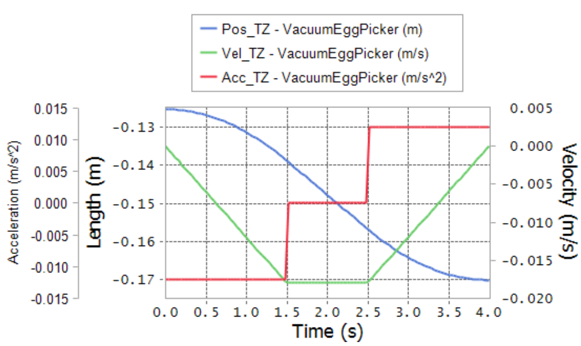


Fig. 7. The motion parameters of Z-axis.

As the figure 7, The motion along Z-axis is operated by a pneumatic cylinder.

The utilization of electric actuators in motion control allow for the storage and execution of multiple target positions, thereby enabling multi-point operation. Additionally, the use of modified motion profiles, such as S-curves, can effectively minimize vibration and shock loads. In contrast, pneumatic actuators typically require a hard stop and spring, and it can be challenging to maintain a consistent set speed or force when utilizing compressed air[17]. As a result, the motion of the Z-axis is typically calculated according to a trapezoidal profile. The acceleration of the Z-axis is set at 0.012 ms^{-2} for a 2 second acceleration time.

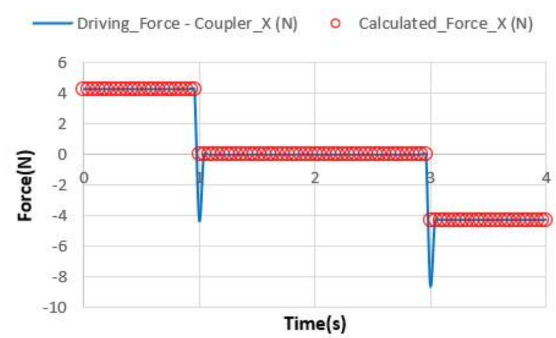
5. RESULTS AND DISCUSSION

The multibody dynamic analysis simulation in RecurDYN is performed with both trapezoidal and S-curved motion profile for 4 second simulation time divided into 200 equal time steps.

The theoretical dynamic analysis by Euler-Lagrange method is performed by calculating in MATLAB using the same input parameters (accelerations of motion profiles and masses of components) as in simulation environment into Equations (16).

```
function [F1,F2,F3] = cartesianDynamic(q1dd,q2dd,q3dd)
    m1 = 10.13;    m2 = 1.26;    m3 = 2.8;
    g = -9.80665;
    F=[m1+m2+m3 0 0; 0 m2+m3 0; 0 0 m3]*[q1dd; q2dd; q3dd]+[0; 0; m3]*g;
    F1=F(1);
    F2=F(2);
    F3=F(3);
end
```

Fig. 8. The function written in MATLAB to calculate theoretical dynamic analysis.



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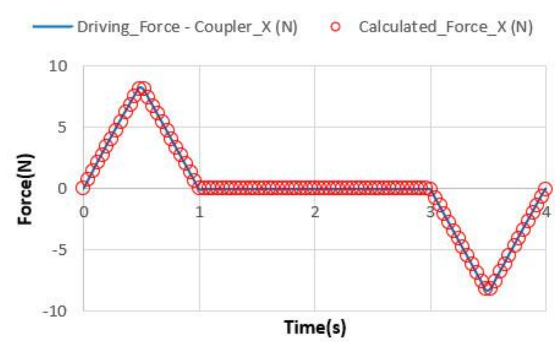


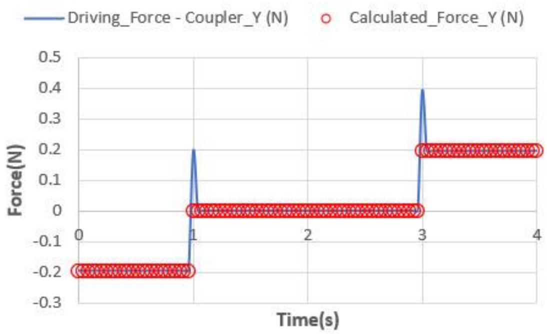
(b)

Fig. 9. Comparisons of resulted forces for X-axis from the multibody dynamic analysis by RecurDYN and the theoretical dynamic analysis using Euler-Lagrange method with (a) trapezoidal motion profile and (b) S-curve motion profile.

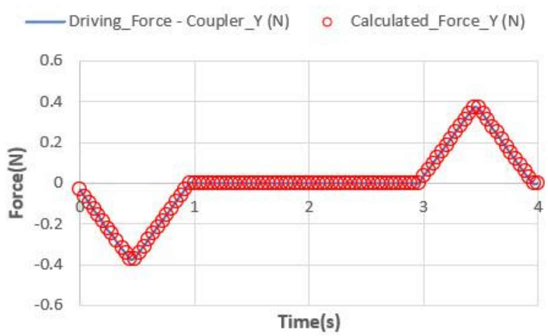
According to the characterization of robot by joint type, the gantry robot can be defined as 3p robot with 3 prismatic joints. And the motion equation for it, the Equation (15) take the linear acceleration and return forces required to generate by the actuators.

Therefore, the simulation model can be verified by comparing its force curves with the resulting force curves from the theoretical dynamic analysis.

Comparisons of forces at the three joints are shown in Figure (9) and (10).



(a)



(b)

Fig. 10. Comparisons of resulted forces for Y-axis from the multibody dynamic analysis by RecurDYN and the theoretical dynamic analysis using Euler-Lagrange method with (a) trapezoidal motion profile and (b) S-curve motion profile.

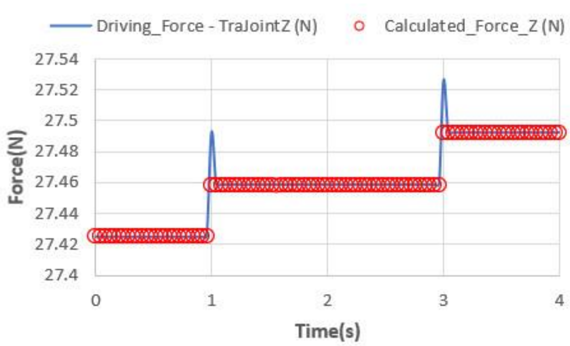


Fig. 11. Comparisons of resulted forces for Z-axis from the multibody dynamic analysis by RecurDYN and the theoretical dynamic analysis using Euler-Lagrange method with trapezoidal motion.

As shown in Figure 9, 10 and 11, the forces resulting from theoretical calculation and simulation are almost identical. In Figure 9(a) and 10(a), the sudden jumps of acceleration at the changing points of the simulation results can be found.

6. CONCLUSIONS

By comparing the simulation results from RecurDYN with the theoretical results from the Euler-Lagrange formulation, it is found that the forces occurring on the joints are almost identical except for the abrupt jerk motions that only appears in the simulation result with trapezoidal motion profile. It means that the S-curve profile is preferable to make the motion control more robust and stable. As a result, the simulation model is reliable and can be used to predict the dynamic behaviors of the gantry robot including actuator sizing appropriate for the desired operating speed and payload. Therefore, the presented simulation method can be used to analyze the behavior of the system prior to the physical development and reduce cost by minimizing possible errors.

ACKNOWLEDGEMENTS

All the authors of the research paper are highly acknowledged to Mechanical Engineering Department, Mandalay Technological University, Myanmar for encouraging and supporting to do this research.

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