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Design and Motion Analysis of 14 Links One Degree of Freedom Delta Parallel Robot

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Abstract A comprehensive design and motion analysis of a 14-link one degree of freedom Delta parallel robot was carried out, a novel robotic mechanism with potential applications in precision assembly, 3D printing, and surgical robotics. The design process begins with number synthesis, which determines the optimal combination of links and link types to achieve the desired degree of freedom. A detailed CAD model is then created using SolidWorks, and motion simulation is performed to analyze the robot's kinematic behavior. The degree of freedom is verified using Gruebler's equation, and the control system properties are analyzed using Simulink, revealing a stable system with a resonant frequency of 10 rad/s. The results demonstrate precise motion during the 5 seconds motion analysis period and the 10 seconds simulation period, making the Delta parallel robot a promising candidate for tasks requiring high accuracy and speed. The transfer function of the robot open loop control system was generated and the represented in a plot, which corresponded with the stability of the system as indicated by the root locus plot. This paper provides a thorough understanding of the design and mechanics of Delta parallel robots, contributing to the development of parallel robotics, standing in line with the demand of comprehensive academic materials for beginners in mechanics and robotics as well as undergraduate students of engineering.

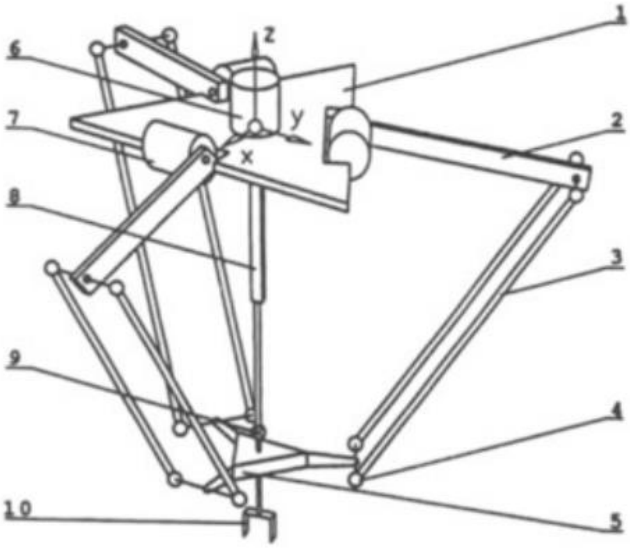
Keywords Design, Robotics, Synthesis, Simulation, Kinematics

1. Introduction

A delta parallel robot is a precise and efficient robotic mechanism, ideal for intricate tasks, as described by Bonev (2001). It consists of three or more parallel arms connected to a shared base and platform, and can handle over 100 parts per minute. Equipped with advanced vision technologies, delta robots can identify and select objects of various colors, shapes, and sizes, making them suitable for assembly, packaging, and material handling tasks. Their lightweight design and consistent performance make them a popular choice in industrial settings.

Parallel robots have become widely used in modern industries, particularly for high-speed pick and place applications, often incorporating automatic visual inspection (Clavel and Raymond 1990). The concept of parallel robots' dates back to the 1920s, with the introduction of spherical parallel robots by James E. Gwinnet (1928). Over the years, improvements were made, and these robots found applications in various fields. In 1965, Stewart proposed a 6-degree-of-freedom parallel robot for use as an aircraft simulator (Stewart 1965). The development of parallel robots has continued, resulting in current classifications of these mechanisms Zarebidoki et al., (2022). Parallel robots can be employed across diverse industries and for various purposes, including machine tools, 3D printing, medical rehabilitation, construction, and numerous other applications Deabs et al. (2021).

The Delta robot was designed as a response to a challenge observed in a chocolate factory in 1985 (Clavel and Reymond, 1990). The manual palletization of chocolates was a monotonous and stressful task for human workers, and existing industrial robots were inadequate for the task Lowe et al., (2023). Therefore, a new design was explored, leading to the development of the Delta robot.



1	Base plate
2	Arm
3	Forearm
4	Spherical joint
5	Travelling plate
6	Actuator of axis #4
7	Actuator of axis 1-3
8	Telescopic transmission
9	Universal joint
10	Gripper

Figure 1.0: A labelled Delta Parallel Robot.

Figure 1.0 depicts the angular Delta robot, where the base plate (1) serves as a stationary foundation for the entire robot structure. It houses the four motors responsible for actuating the four degrees of freedom (6 & 7) of the structure. The connection between the base plate (1) and the traveling plate (5) is established through three kinematic chains. Each chain consists of an arm (2) and a forearm (3). To ensure lightweight construction without backlash, the forearms are constructed using two parallel rods instead of universal joints, which are challenging to achieve under such requirements. It is worth noting that each forearm forms a parallelogram. The combined effect of the three kinematic chains ensures that the traveling plate remains parallel to the base. The components in the diagram are labeled as follows: 1 - Base plate, 2 - Arm, 3 - Forearm, 4 - Spherical joint, 5 - Traveling plate, 6 - Actuator of axis #4, 7 - Actuator of axis #3, 8 - Telescopic transmission, 9 - Universal joint, 10 - Gripper.

The Delta robot's design is based on the use of parallelograms, which enables the maintenance of a fixed orientation between input and output links, resulting in three purely translational degrees of freedom. The robot's design, with base-mounted actuators and lightweight links, allows for high accelerations, making it suitable for pick and place operations involving lightweight objects, and typically operates within a cylindrical workspace.

The marketing history of the Delta robot dates back to 1983 when Swiss Brothers Marc-Olivier and Pascal Demaurex established Demaurex, a company that commercialized the Delta robot for the packaging industry. Over the years, Demaurex successfully established a prominent position in this challenging new market, selling approximately 500 Delta robots worldwide, and licensing the technology to various companies, including Hitachi Seiki.

The Delta robot's design is based on the use of parallelograms, which enables the maintenance of a fixed orientation between input and output links, resulting in three purely translational degrees of freedom. The robot's design, with base-mounted actuators and lightweight links, allows for high accelerations, making it suitable for pick and place operations involving lightweight objects, and typically operates within a cylindrical workspace.

2. Methodology

2.1 Number Synthesis

The number synthesis of 14 links mechanism was done for the determination of all possible combination of links and link type with 1 degree of freedom, and to choose the particular combination that will be best in the design of the Delta parallel robot. The number synthesis analysis was conducted using equation 2.1 and 2.2 below,

$$L - 4 = T + 2Q + 3P + 4H \quad (2.1)$$

$$L = B + T + Q + P + H \quad (2.2)$$

Where,

L is number of links

B is number of binary links
T is number of ternary links
Q is number of quaternary links
P is number of pentagonal links
H is number of hexagonal links

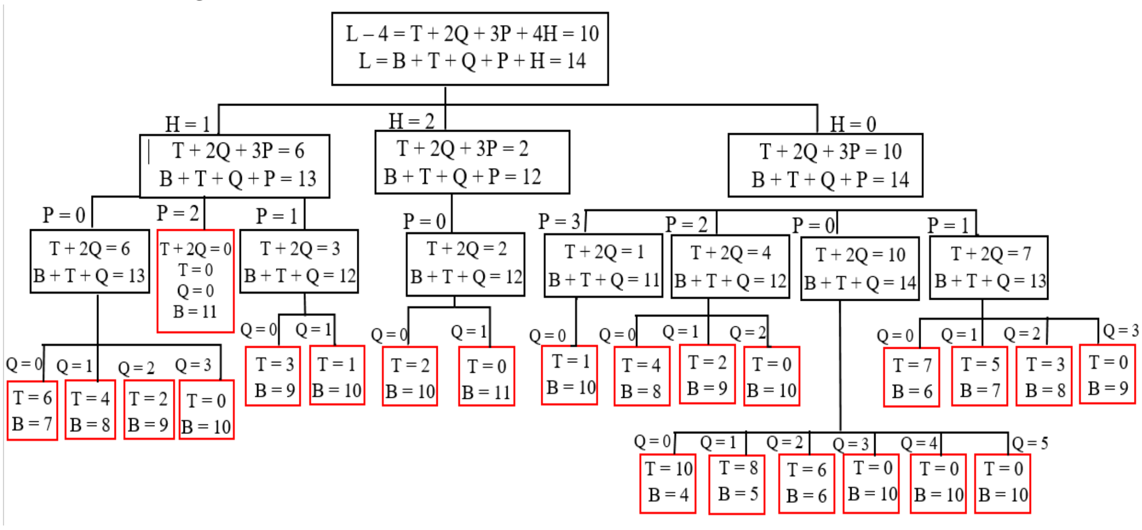


Figure 2.1: Number synthesis of possible combination of links of 14 links mechanisms with 1 DOF

NB: The ones on red box marks the end of combination under each condition

2.2 Design and Analysis

After number synthesis was conducted to determine the number of links and type of link that will best suit the desired mechanism, SolidWorks will be used in designing separately all the possible links that will be deduced from number synthesis analysis, thereafter, it will be assembled and simulated from motion analysis.

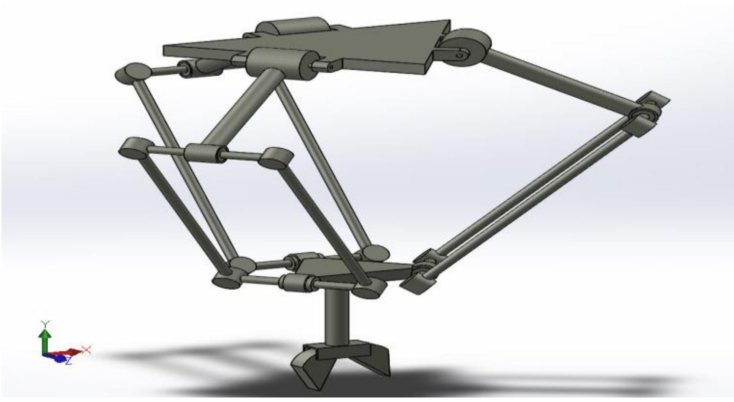


Figure 2.2: Isometric view of the Delta parallel Robot in SolidWorks

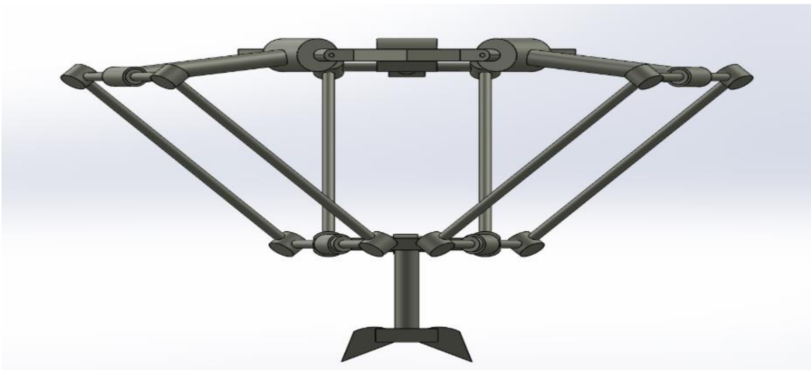


Figure 2.3: Front view of the Delta parallel Robot in SolidWorks

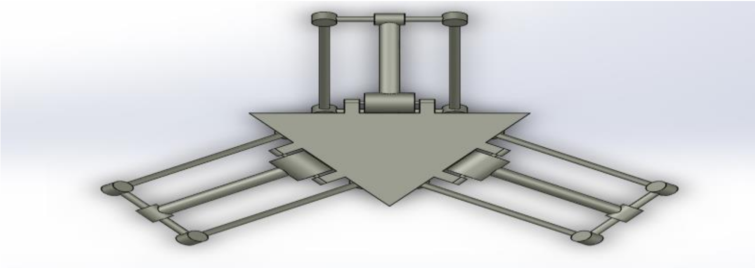


Figure 2.3: Top view of the Delta parallel Robot in SolidWorks

The Delta Parallel Robot mechanism is a 14 links mechanism, consisting of 7 binary links, 4 ternary links, and 3 quaternary links. Motion study was conducted after the design to get the motion parameters of the moving parts.

2.3 Degree of Freedom Analysis

The Mechanism Will be subjected to Gruebler's equation to ascertain that the degree of freedom is one using equation 2.3,

$$M = 3(L-1) - 2J \qquad (2.3)$$

Where M is mobility or degree of freedom

3. Results and Discussion

Table 3.1: Number synthesis table of 23 combinations of links for 14 links mechanisms

S/N	L	B	T	Q	P	H
1	14	7	4	3	0	0
2	14	10	0	3	0	1
3	14	7	6	0	0	1
4	14	8	4	1	0	1
5	14	9	2	2	0	1
6	14	11	0	0	2	1
7	14	10	2	0	0	2
8	14	11	0	1	0	2
9	14	8	4	0	2	0
10	14	9	2	1	2	0
11	14	10	0	2	2	0
12	14	9	3	0	1	1
13	14	10	1	1	1	1
14	14	10	1	0	3	0
15	14	4	10	0	0	0
16	14	5	8	1	0	0
17	14	6	6	2	0	0
18	14	6	7	0	1	0
19	14	7	5	1	1	0
20	14	8	3	2	1	0
21	14	9	1	3	1	0
22	14	9	0	5	0	0
23	14	7	4	3	0	0

After the above number synthesis, S/N. 23 was chosen for the design of the Delta Parallel Robot mechanism as it best suits the desired number of links and link type for the design which is 7 binary links, 4 ternary links, and 3 quaternary links.

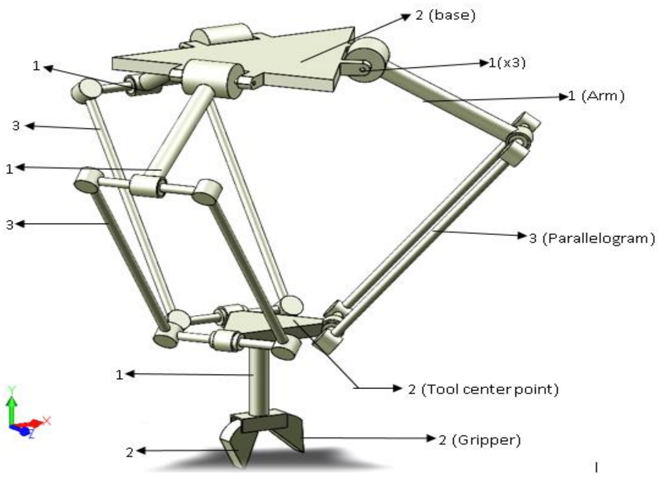


Figure 3.1: Labelled image of delta parallel robot

Table 3.2: Link Description

No.	Link	Quantity
1	Binary	7
2	Ternary	4
3	quaternary	3

3.1 Degree of Freedom Analysis

From the Gruebler's equation in equ 2.3

M = 3 (L-1) – 2J,

From figure 5 we have 19 joints and total of 14 number of links

M = 3 (14 – 1) – 2(19)

M = 39 – 38 = 1

3.2 Table of Values and Graphs from Motion Analysis

Table 3.3: Table of values from delta parallel robot motion analysis simulation in SolidWorks

Time (sec)	Linear Displacement of the Toolcenter point (mm)	Linear Velocity of the Tool center point (mm/sec)	Angular Velocity of the Gripper (deg/sec)	Angular Velocity of the Parallelogram (deg/sec)	Angular Accelerationof the Parallelogram (deg/sec^2)	Angular Velocity of the Arm (deg/sec)	Angular Acceleration of the Arm (deg/sec^2)
0	400.8145179	50.000000000	9.6	23.77574507	63.93785631	39.312212	104.396019
0.2	391.1749253	50.000000000	9.870974839	16.4896955	21.44391101	27.534832	34.1315246
0.4	381.5538843	50.000000001	10.12312933	13.35533343	11.58037828	22.610569	17.884355
0.6	371.9528345	50.000000000	10.42205218	11.49117728	7.548604386	19.77774	11.2444813
0.8	362.3733648	49.999999999	10.69338974	10.21033467	5.456648598	17.907058	7.78377936
1	352.8172331	50.000000001	10.83784458	9.252711063	4.215772879	16.573387	5.7088137
1.2	343.2863883	50.000000000	10.92705418	8.494981682	3.414810396	15.57669	4.34355443
1.4	333.7829967	49.999999999	11.01803778	7.869953671	2.867780033	14.809188	3.38236916
1.6	324.3094715	50.000000001	11.0979662	7.337304332	2.479713191	14.207286	2.66886963
1.8	314.8685086	50.000000000	11.19078011	6.871004807	2.197732395	13.730989	2.11539768
2	305.4631273	49.999999999	11.27048265	6.453229977	1.990469031	13.353981	1.66917848
2.2	296.0967183	50.000000001	11.35606991	6.07113086	1.838444415	13.058415	1.2964816
2.4	286.7731003	50.000000000	11.40000000	5.714995348	1.729197329	12.832	0.9745639
2.6	277.4965864	49.999999998	11.40000000	5.377132444	1.654661426	12.666278	0.68727028
2.8	268.2720633	50.000000001	11.40000000	5.051154295	1.60969075	12.555589	0.42247622
3	259.1050836	50.000000000	11.40000000	4.731484734	1.591210047	12.496431	0.17051311
3.2	250.0019776	49.999999999	11.40000000	4.412997912	1.597733549	12.487079	0.07688375
3.4	240.9699841	50.000000001	11.40000000	4.090728534	1.629115551	12.527389	0.32733918
3.6	232.0174081	50.000000000	11.40000000	3.759614443	1.686469205	12.618728	0.58846357
3.8	223.1538082	49.999999999	11.40000000	3.414241178	1.772225723	12.764035	0.86844967
4	214.3902203	50.000000000	11.40000000	3.048560279	1.890340858	12.968	1.17673178
4.2	205.739425	50.000000002	11.40000000	2.655549551	2.046677372	13.237387	1.52480337
4.4	197.2162657	49.999999999	11.40000000	2.226773479	2.249635432	13.581559	1.92734075
4.6	188.8380255	50.000000000	11.40000000	1.751782561	2.511161934	14.013264	2.40385221
4.8	180.6248718	50.000000000	11.40000000	1.217255228	2.84836674	14.549833	2.98121665
5	172.600373	49.999999999	11.40000000	0.605721965	3.286176581	15.215037	3.69778692

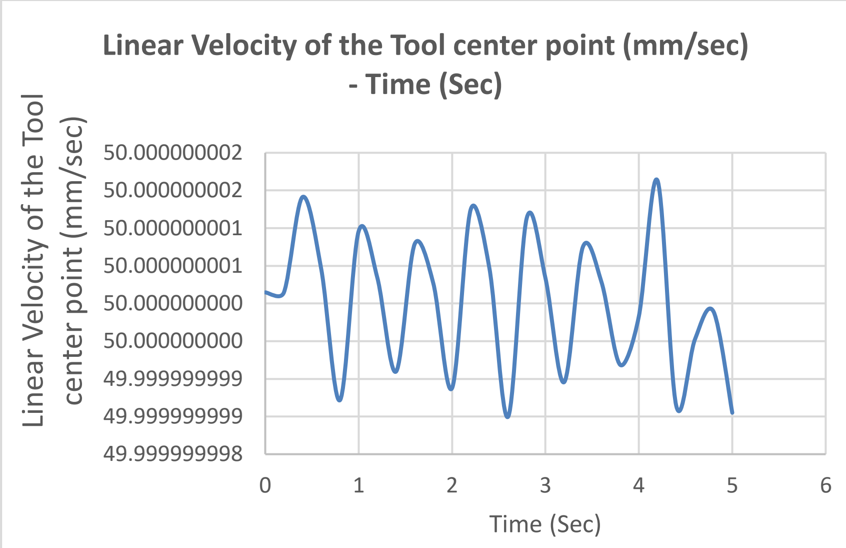


Figure 3.2: Graph Linear Velocity of the tool center point against time

The equation that best describe the graph of Linear velocity of the tool center point – time is **y = -5E-11x + 50**. The linear velocity of the tool center point is the velocity at which it covered the distance from 400.8mm to 172.6mm.

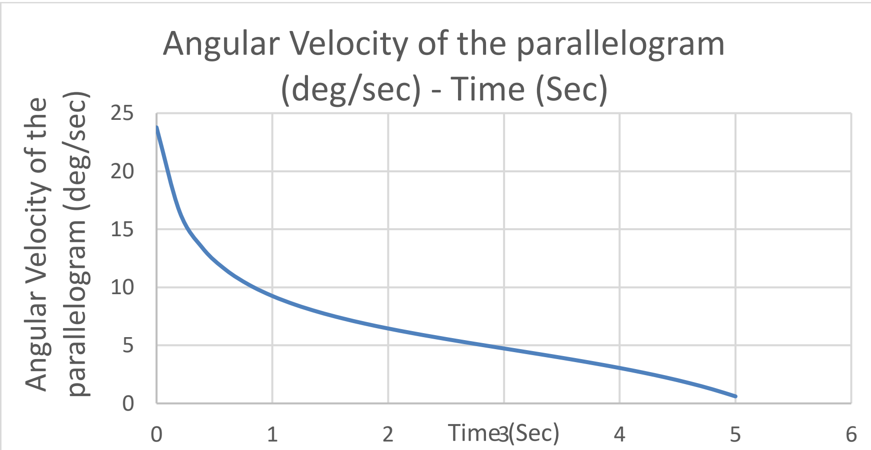


Figure 3.3: Graph Angular Velocity of the parallelogram against time

The equation that best describe the graph of Velocity of the parallelogram against time is **y = -2.9768x + 14.201**. The parallelogram is the part connecting the Arm to the tool center point and allows angular motion that looks like folding

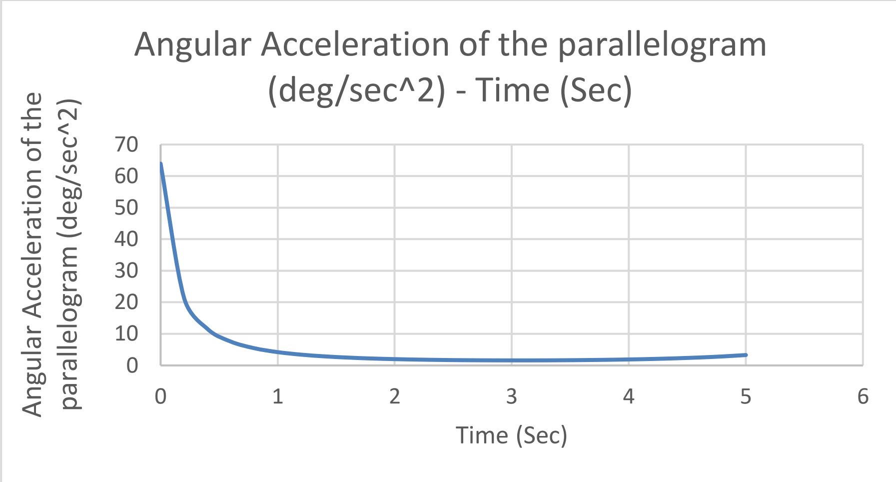


Figure 3.4: Graph Angular Acceleration of the parallelogram against time

The equation that best describe the graph of Angular Acceleration of the parallelogram against time is **y = -4.0631x + 16.199**. This graph shows how the angular acceleration of the parallelogram changes within the period of 5 sec.

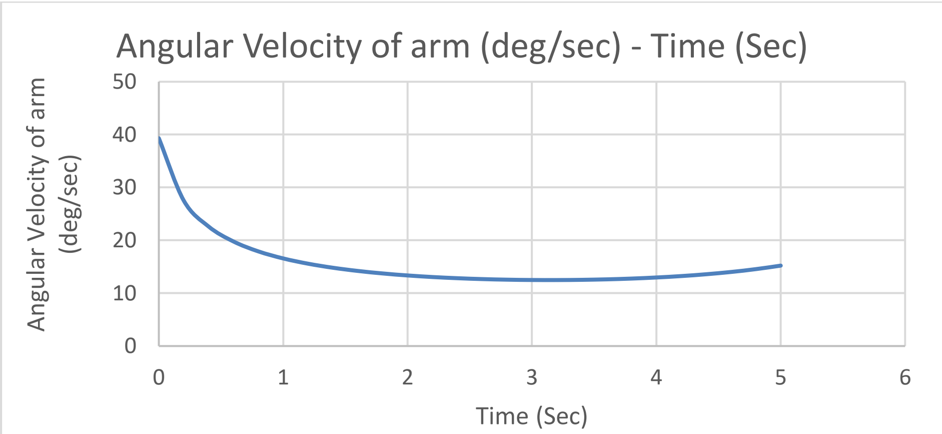


Figure 3.5: Graph Angular Velocity of arm against time

The equation that best describe the graph of Angular Velocity of arm against time is **y = -2.4329x + 21.966**. The arm is the part that is connected and controlled by the actuator. The above graph shows how angular velocity of the arm changes in period of 5 sec

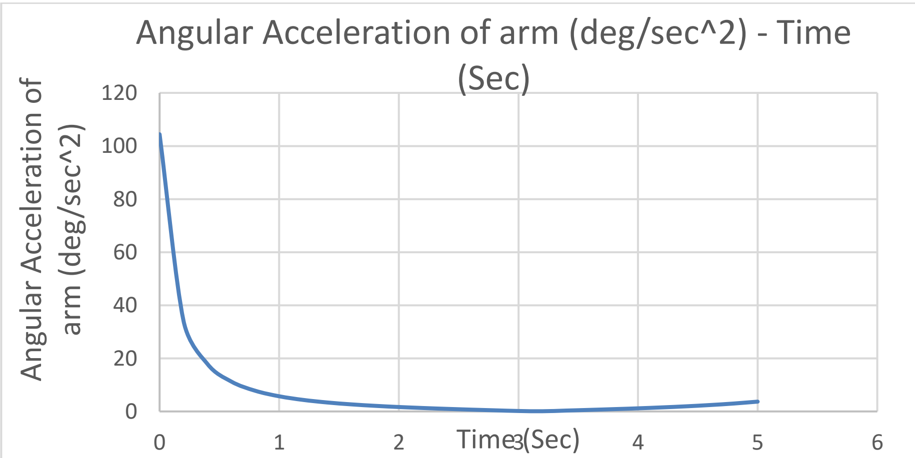


Figure 3.6: Graph Angular Acceleration of arm against time

The equation that best describe the graph Angular Acceleration of arm against time is **y = -6.8924x + 25.479**. This is the acceleration of the arm as it displaces from 0 sec to 5 sec

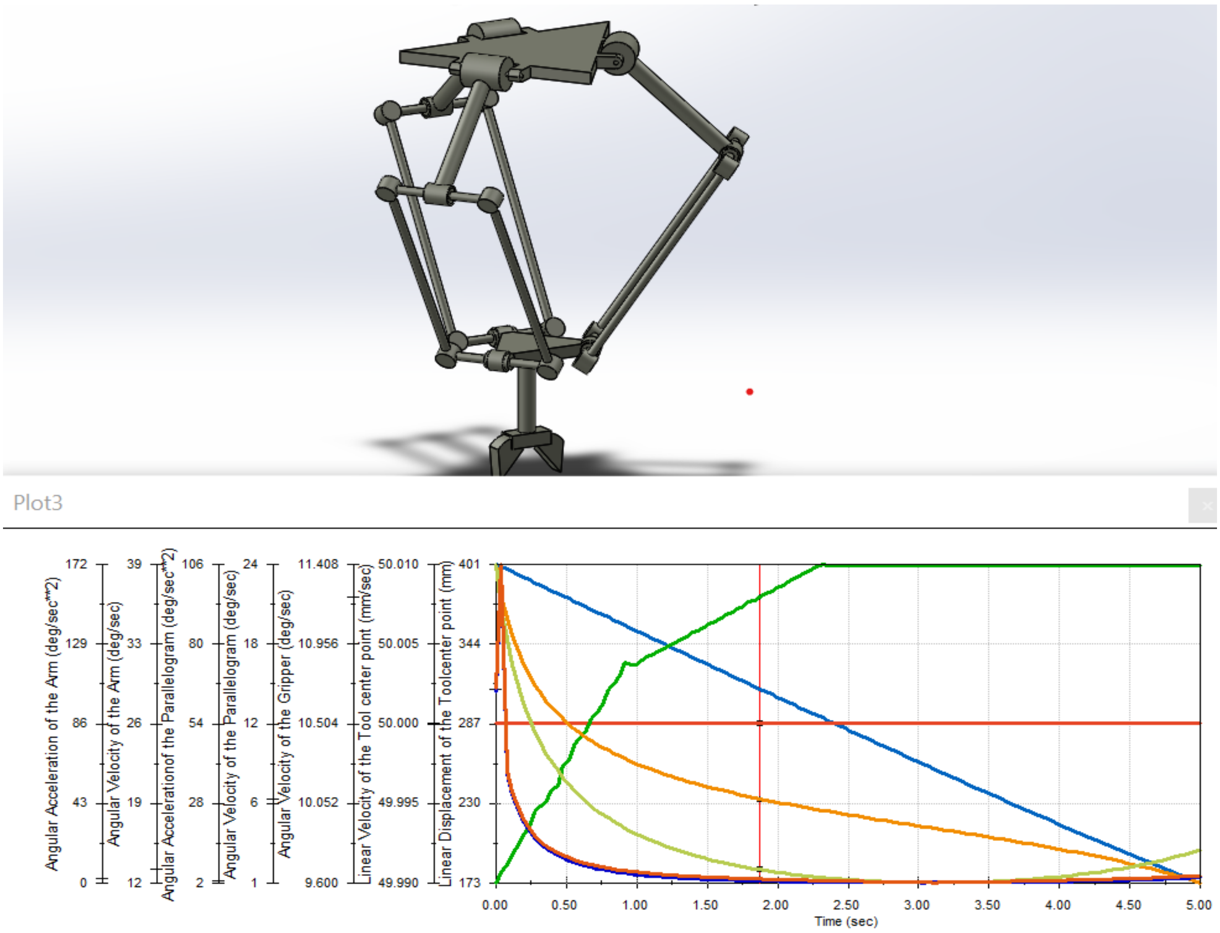


Figure 3.7: SolidWorks Motion simulation of the Delta parallel robot containig composite graph

After the SolidWorks motion simulation was done for a period of 5 seconds to determine the characteristics of the parallel robot. As the tool center point displaces linearly from a height of 400.8mm down to 172.6mm, it maintained a nearly constant linear velocity of 50mm/sec with a little variation of ± 10-9 mm/sec. The gripper rotates at a nearly constant angular velocity of 9.6 °/sec with a variation of about ± 10-9. The angular velocity and the acceleration of the parallelogram and the angular velocity and acceleration of the arm all decreased.

3.3 Simulink Modelling

The Delta parallel robot Solidworks CAD model was exported via Simscape multibody link, and the “xml” file was created which was later imported to the MATLAB environment and subsequently used to create the Simulink block of the robot, and analysed in Mechanics explorer interface as shown below in fig 3.8, and fig 3.9.

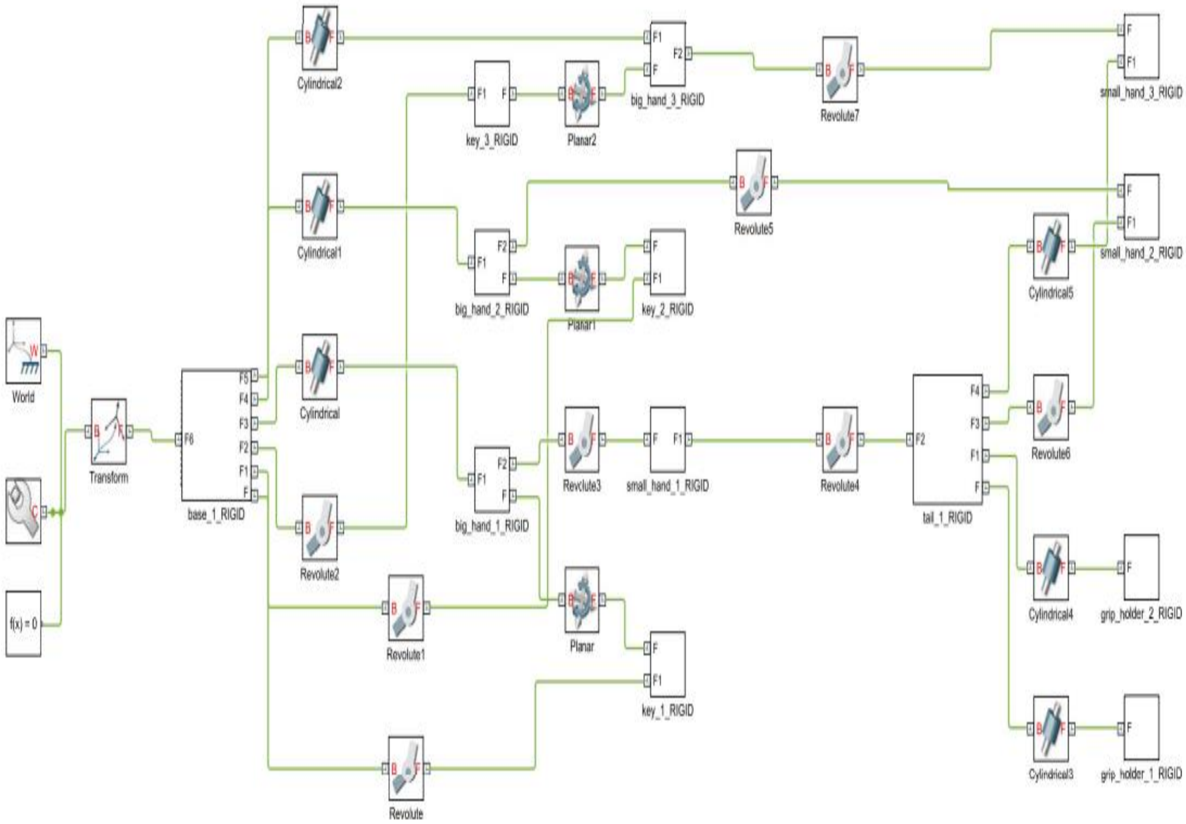


Figure 3.8: Simulink Block of the Delta Parallel Robot

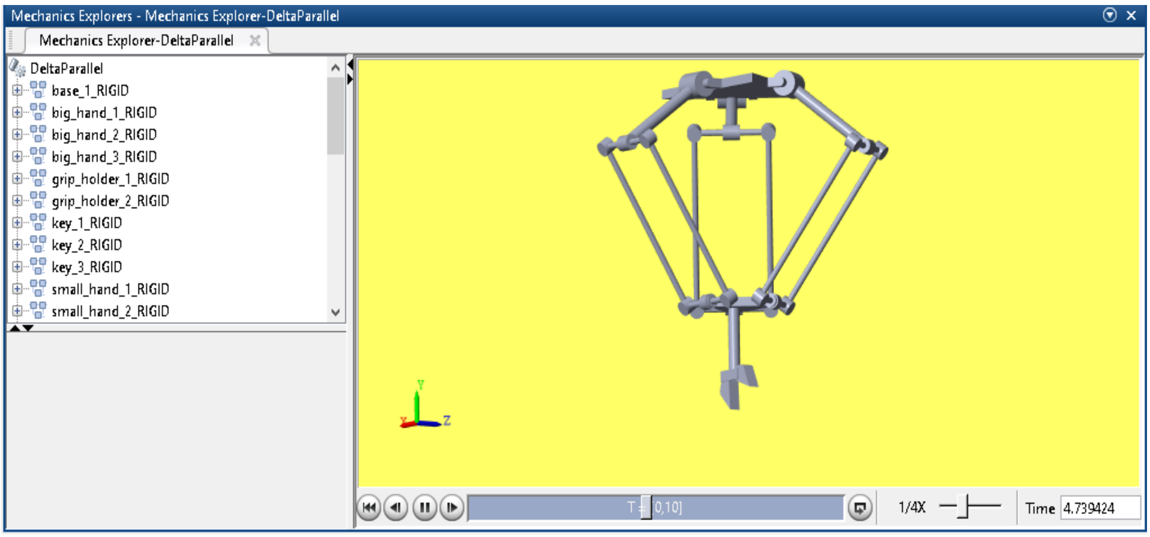


Figure 3.9: Delta Parallel Robot in Simulink Mechanics Explorer Interface

3.4 Transfer Function

Transfer function is the ratio of the output signal to the input signal of a system. Transfer function contains dynamic information about a system (Ahmed A. S. 2007). When expressed by the Laplace transform it can be used to explain the stability of the system.

- Step 1: Using the Motion analysis result from SolidWorks as represented in table 3.3, we applied the linear displacement of the tool center, in the time domain [y(t)], as the input function of the system, plot in MATLAB and derive the equation of the best fit curve using linear fitting.

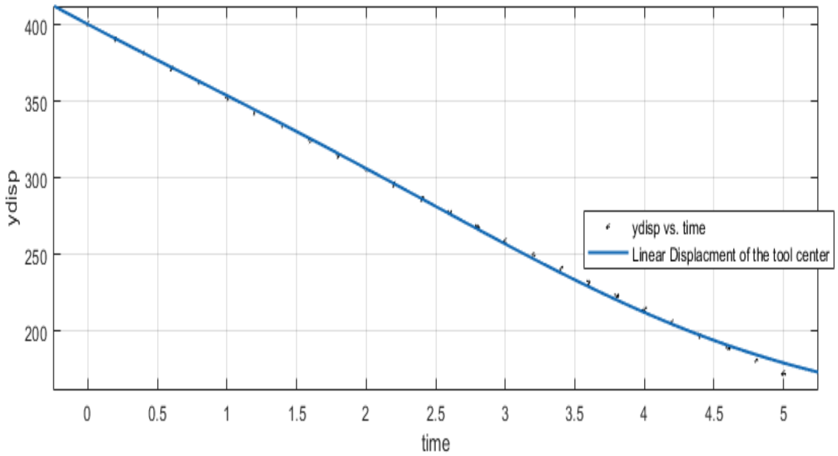


Figure 3.10: Curve fitting of the tool center linear displacement

Linear model:

y(t) = a*(sin(t-π)) + b*((t-10)2) + c

Coefficients (with 95% confidence bounds):

a = -8.711 (-10.64, -6.78)

b = 2.839 (2.778, 2.9)

c = 116.6 (113.1, 120.1)

Goodness of fit:

SSE: 119.6

R-square: 0.999

Adjusted R-square: 0.9989

RMSE: 2.28

- Step 2: We repeated the same process as in step 1 using the angular velocity of the gripper as the output [ω(t)]

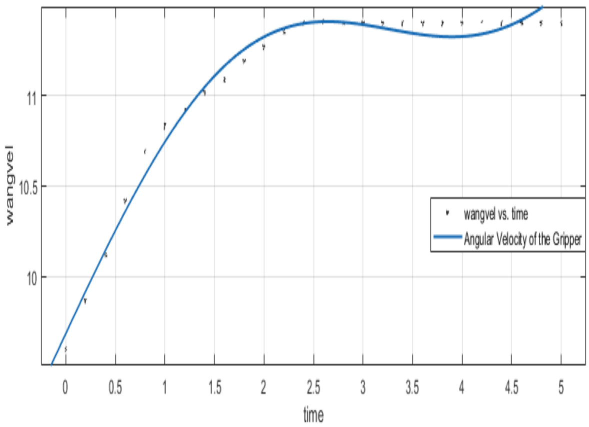


Figure 3.11: Curve fitting of the gripper angular velocity

Linear model:

ω(t)= a*(sin(t-π)) + b*((t-10)^2) + c

Coefficients (with 95% confidence bounds):

a = -0.5357 (-0.5944, -0.477)

b = -0.03195 (-0.03381, -0.0301)

c = 12.88 (12.77, 12.99)

Goodness of fit:

SSE: 0.1103
R-square: 0.9838
Adjusted R-square: 0.9824
RMSE: 0.06926

- Step 3: We derived the Laplace transform of the input [Y(s)] and output [W(s)] equations using MATLAB command "laplace(f(t))".

Input: y(t) = -8.711 *(sin(t-π)) + 2.839*((t-10)2) + 116.6

$$Y(s) = \frac{400500*S^4 + 48069*S^3 + 1406178*S^2 + 56780*S + 5678}{1000*S^3(S^2+1)}$$

Output:

ω(t)= -0.5357*(sin(t-π)) + -0.03195*((t-10)^2) + 12.88

$$W(s) = \frac{96850*S^4 + 11747*S^3 + 96211*S^2 + 6390*S - 639}{10000*S^3(S^2+1)}$$

- Step 4: We obtained the transfer function [G(s)] by dividing the Laplace transform of the output W(s), by the Laplace transform of the input Y(s).

$$G(s) = \frac{W(s)}{Y(s)}$$

$$G(s) = \frac{96850*S^4 + 11747*S^3 + 96211*S^2 + 6390*S - 639}{10(400500*S^4 + 48069*S^3 + 1406178*S^2 + 56780*S + 5678)}$$

The Transfer Function of the system was modelled in the Simulink environment and the behavior of the system represented in the scope output.

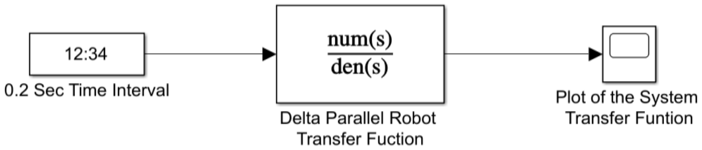


Figure 3.12: Block diagram of the Robot Open loop system

The block diagram shows the open loop control system of the Delta Parallel Robot.

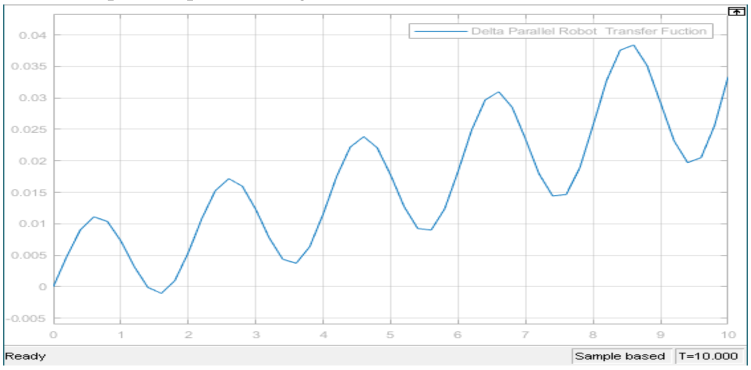


Figure 3.13: Transfer Function of the Open loop system of the Delta Parallel Robot

Other important information of a control system was also modelled for the Robot and the result presented below.

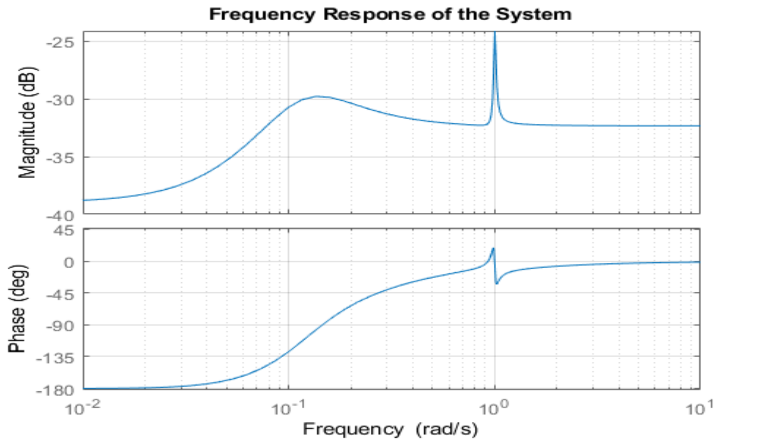


Figure 3.14: Frequency Reponses of the Delta Parallel Robot control

The frequency response of the Delta parallel robot control reveals the system's ability to track commands and respond to disturbances across various frequencies, showcasing its stability and performance. The plot generated using MATLAB displays the gain magnitude and phase margin angles, resonant peaks at 1 rad/s, and cutoff frequencies at 10 rad/s, providing insights into the controller's effectiveness and potential areas for optimization.

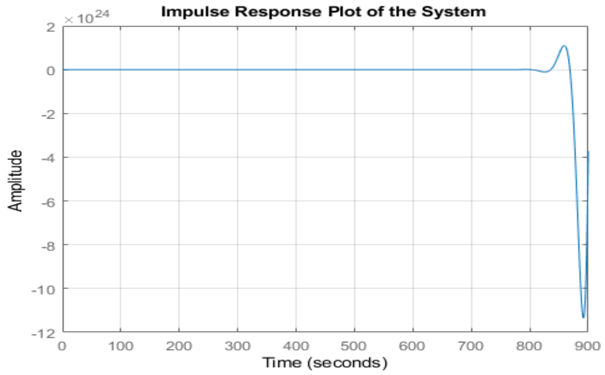


Figure 3.15: Impulse response of the Delta Parallel Robot control

The impulse response of the Delta parallel robot control reveals how the system responds to a sudden, brief input or disturbance, showcasing its ability to absorb and recover from the impulse. The plot displays the transient behavior of the robot's end-effector or joints over time, providing insights into the system's stability, settling time, and ability to track desired trajectories.

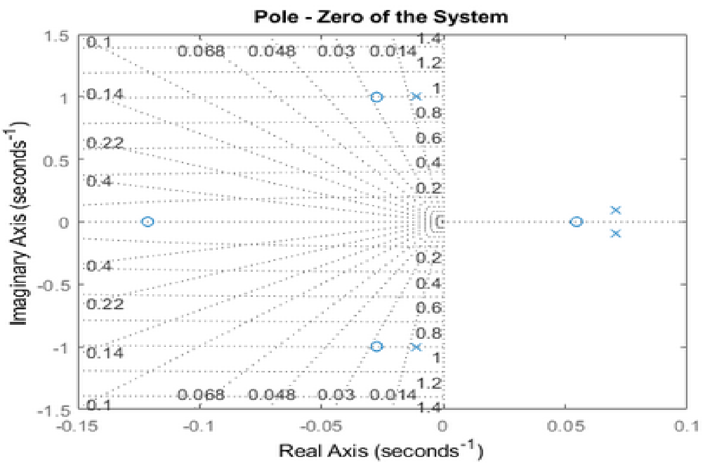


Figure 3.16: Poles and Zeros of the Delta Parallel Robot control

The plot exhibits a distinctive "V" shape formed by the poles in the left-half plane, with the point of the "V" situated at approximately (0.07,0), indicating a dominant stable mode. The zeros, located at (0,0), and (0.03, ±0.04) form a symmetrical pattern about the origin, suggesting a resonant frequency at 1 rad/s and 10 rad/s, respectively.

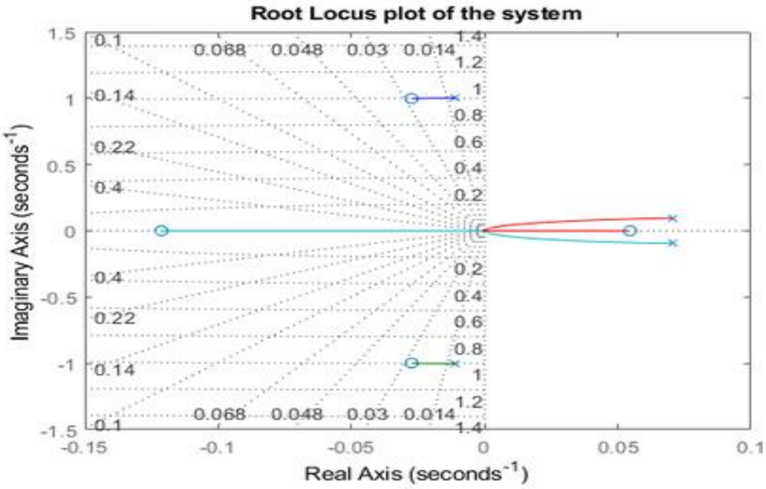


Figure 3.17: Root Locus of the Delta Parallel Robot control

The Root Locus plot reveals the trajectory of the system's poles as the gain parameter varies, displaying a complex pattern of branches that intersect and diverge, indicating changes in stability and dynamic behavior. The plot shows the roots originating from the open-loop poles and terminating at the open-loop zeros, with some branches crossing into the right-half plane, indicating potential instability and highlighting the need for careful control design.

4. Conclusion

A 14-link one degree of freedom Delta parallel robot, consisting of 7 binary links, 4 ternary links, and 3 quaternary links was successfully designed and analyzed. Through number synthesis, we determined the optimal combination of links and link types, and used SolidWorks to design and simulate the robot's motion. We verified the robot's degree of freedom using Gruebler's equation (M = 3(L-1) - 2J) and confirmed that the mechanism has one degree of freedom. Our results showed that the Delta parallel robot achieves precise motion with a linear displacement of 228.21 mm for the tool center and an angular velocity of 15.21 rad/s for the gripper within a 5 seconds simulation period. The frequency response plot indicated a stable system with a resonant frequency of 10 rad/s, and the root locus plot confirms the system's stability. These findings demonstrate the potential of Delta parallel robots for precise and efficient motion in applications such as pick-and-place assembly, 3D printing, and surgical robotics. This comprehensive review of the design and mechanics of Delta parallel robots contributes to the understanding of undergraduate engineers and provides a foundation for further research and development in parallel robotics. Future work includes experimental validation of the robot's performance using a physical prototype, investigation of control strategies for precise trajectory tracking and motion control, and extension of the design to include additional degrees of freedom or complex tasks.

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