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Development of Fourth Link and its Impact on FDM 3D Printer

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Abstract: This paper presents a new technique for the design and analysis of a fourth link mechanism for a delta-type 3D printing technology. The additional linked elements like connectors, connecting rods, and outer parts are designed as RepRap components for the fourth link assembly operation. At the prototype development stage, a CAD model of the mechanism is created and compared for the abilities and limitations of the existing three links and added link. The major drawback of the motion in Delta printers includes the determination of mechanism mobility (DOF), utilization of working space, and printing speed. The approaches that can be considered are presented for the modification of the new model 3D printer. For the next part, a fourth link is added along with the existing three links. The steps required in the analysis are checked on the inverse kinematics movement, through dynamic conditions in means of a jerk, velocity, and acceleration. For the static conditions in means of stress, strain, and displacement of links and joints, and graphs attached to both mechanisms. The model is checked out with the coefficients of error for the mechanism with unknown absolute angular velocities, accelerations, and jerks, determined based on the working of the module. Thus, the performance of the existing three pairs of links and the added link automates the printing activities in an effective way. The addition of the fourth link is studied and checked out with considerations for the quality of the printed products. Hence, this work attempts to introduce a new link along with the existing three links of Delta printers.

Keywords: Delta, Additive Manufacturing, 3D printer, Computer-Aided Design.

I. INTRODUCTION

3D printing on the intricate surface is constructed on the distinctive characteristics of the superior error tolerance along with the printing path. After creating the prototype of the conformal printer, the engagements and error conditions are digitalized.

In instruction to shorten the calculation progression with an unconditional value mark, a “circulation substitute” calculation technique has been anticipated by the enumeration process to undertake all the positive and negative circumstances, by streamlining and operating the matched optimal interpretation instantly. Then the inverse position kinematics interpretation is consequent in closed-system, where the forward position kinematics problem is disentangled through an iterative process prior. The velocity, acceleration and jerk analyses are accomplished, and the individuality configurations including three types of conventional individualities and the constraints are checked. Then, we can judge whether the optimal solution of adding a new link meets the conditions by taking the motion as the corresponding criterion. If not, the next assuming situation should be calculated until the solution is consistent with the assumption.

II. ESSENTIAL NEEDS FOR INTRODUCING THE FOURTH LINK

By monitoring the movement of the printing platform, the fault diagnosis of the whole transmission can be indirectly achieve. By comparing with a point-by-point and non-optimized trajectory, layer-by-layer optimization would result in smoother behavior that can improve the quality of the printing.

The average reduction in geometric error turns out to be around 20.89% and 12.32%, respectively, which has demonstrated a higher level of precision enhancement through geometric error reduction. In particular, when a mechanism is not statically balanced, the weight of the linkage produces force or torque at actuators under static conditions and should contribute to supporting the weight of the moving links for any configurations. The optimization of process parameters is a major challenge for dimensional accuracy, surface roughness, parts strength, and build time parts improvement. A great deal of work has been carried out and reported in the literature on the static balancing problem.

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The proposed system is based on the fact that the non-rotating moving platform provides the proper reference for the spring attachment points, that otherwise need to be constructed using auxiliary parallelograms or similar. Here, each leg is connected at one end to the guideway by a universal joint and at another end to the moving platform by a spherical joint. While the kinematics and dynamics model of this manipulator were derived, static balancing was not studied. It was chosen by drafting the new model to distribute the load of the platform mass equally among the limbs of the manipulator. This results in the least additional load on the links. Therefore the mass can be distributed arbitrarily among the limbs.

In this paper, the static balancing of the four-degree-of-freedom platform type parallel manipulator with the fixed-length legs shown in Fig. 1 is studied and modified. In such a case, a method is proposed to solve this problem. This system consists of a Moving Platform (MP) to which an additional link is attached, where three legs slide along the fourth guideway that is mounted on the support structure. Based on the proposed method, the mechanism can be balanced using the counterweight with a smart design of the pantograph mechanism along with the Base Platform (BP). With this design, it is possible to obtain a constant global center of mass for any configurations of the manipulator.

III. DESIGN OF EXISTING AND NEW MODEL

The design of the delta model is drafted using CAD software, where the actual model with the required dimensions is developed precisely; so that it can be used in the future to print. The design process is started by keeping the links as a basic design parameter. As our aim is to construct a new model in delta type 3D printer, with changes in the existing three links model as shown in Fig 1. This is further expected to develop with the fourth link as shown in Fig 2.

The 3-Dimensional motion is achieved by synchronization of movements in X, Y and Z directions. Instead of XYZ rods, delta printers supports the extruder with three arms, which are attached to three vertical posts arranged in a triangle as shown in Figure 1. Each arm can moves in horizontal and vertical directions, but by moving each arm independently the extruder is able to move in all directions. In the former method, if the center of mass of a mechanism can be made stationary, the static balancing is obtained in any direction of the Cartesian space.

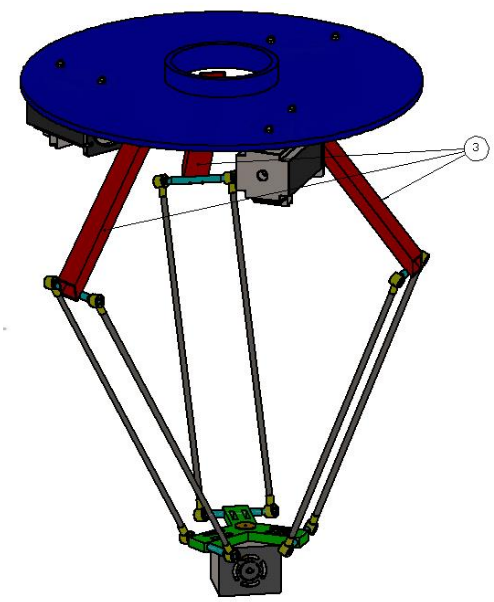

Figure 1. Existing model of three links

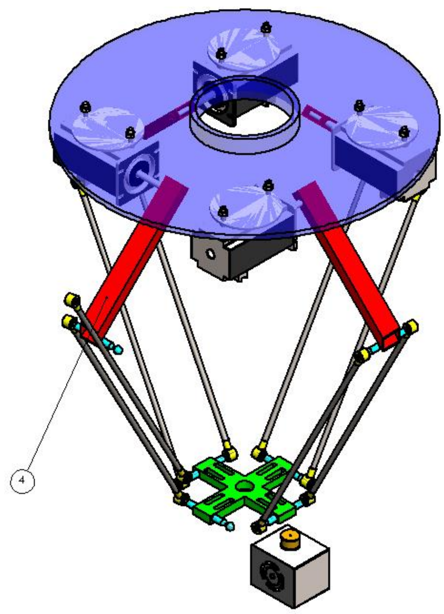

Figure 2. Exploded and transparent view with added fourth link

In the second approach, if the total energy is kept constant, the mechanism is statically balanced only in the direction of gravity vector. As the main objective was to design additional fourth link model than existing one, delta machine is selected which can print any entangled article with required quality such as dimensional accuracy, strength and surface finish. This machine is expected to print objects of 200 microns layer. The mechanism in existing model uses 4 stepper motors, where three for X-axis, Y-axis, Z-axis movement and one for the filament feeding. Whereas, the mechanism in new model has 5 stepper motors, here the extra motor is added to the additional link respectively as shown in Figure 2. However, this transition are expected to improve the additive manufacturing process.

A. Coupler Curve Formation

For the parallel manipulator the work was focused much on the design of gravity compensated of a six-degree-of-freedom parallel manipulator with revolute joints of the existing model. Each leg with two links is connected by an actuated revolute joint to the base platform and by a spherical joints the moving platform. Two methods are used where, one is using the counterweight and the other is by using springs. The math for inverse kinematics can seem pretty daunting, but it comes down to these basic facts for a theoretical calculation.

Three Carriages are mounted on three Towers and together move a single Effector as shown in Figure 3. Taking into account, the physical constraints introduced by cone angle limits of spherical joints and motion ranges of linear actuators, the reachable workspace of the manipulator is generated via numerical search method, and the workspace volume is calculated and compared at various actuator layout angles. Values entered in this calculation are higher than the practical value when tested for the coupler curve. It's done to get the desired value even at higher load conditions than the load at workplace. Diameter of steel shall be used = 2mm (it's the least diameter that can be used, this value is used to check the metal characteristic at lower diameter than our desired diameter).

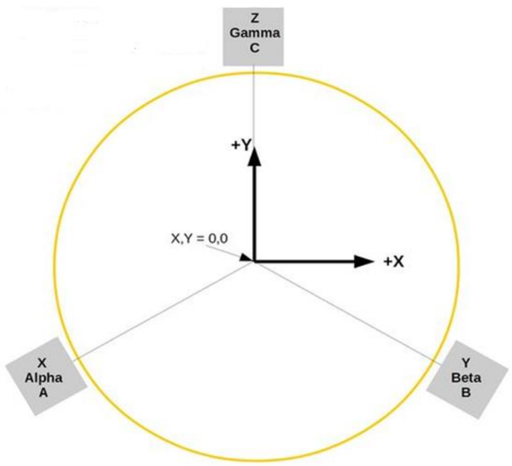

Figure 3. Expected trajectory in existing three links design

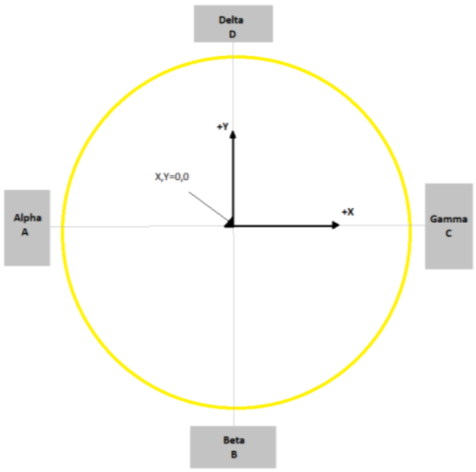

Figure 4. Expected trajectory in new four links design

B. Algorithmic Design Tool

Once we know the distance, we can easily get the carriage Z position:
To start, let us calculate the (x, y) coordinates of the three carriages on the towers. For this we need to know the **DELTA_RADIUS**.

> **DELTA_RADIUS** is calculated from values set for **DELTA_SMOOTH_ROD_OFFSET**, **DELTA_EFFECTOR_OFFSET**, and **DELTA_CARRIAGE_OFFSET** in configuration.

These values are set by directly measuring their lengths on the printer.

DELTA_RADIUS = 90
DELTA_SMOOTH_ROD_OFFSET - DELTA_EFFECTOR_OFFSET - DELTA_CARRIAGE_OFFSET

From **DELTA_RADIUS** we can calculate the x and y position of the three carriages on the towers:

delta_tower1_x = DELTA_RADIUS * cos(210)
= DELTA_RADIUS * cos(180 + 30)
= - DELTA_RADIUS * cos(30)
= - DELTA_RADIUS * sin(60)
delta_tower1_y = DELTA_RADIUS * sin(210)
= DELTA_RADIUS * sin(270 - 60)
= - DELTA_RADIUS * cos(60)
delta_tower2_x = DELTA_RADIUS * cos(330)
= DELTA_RADIUS * cos(30)
= DELTA_RADIUS * sin(60)
delta_tower2_y = DELTA_RADIUS * sin(330)
= - DELTA_RADIUS * sin(30)
= - DELTA_RADIUS * cos(60)

delta_tower3_x = 0

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delta_tower3_y = DELTA_RADIUS
Now, to form the fourth link to (x, y, z), we need to use some simple trigonometry to calculate the values of Z on the three towers:
DELTA_DIAGONAL_ROD^2 = delta_tower1_z^2 + (distance of carriage on tower1 from x, y)^2
delta_tower1_z = sqrt(DELTA_DIAGONAL_ROD^2 - (delta_tower1_x - x)^2 - (delta_tower1_y - y)^2)
Taking the given z into account:
delta_tower1_z = sqrt(DELTA_DIAGONAL_ROD^2 - (delta_tower1_x - x)^2 - (delta_tower1_y - y)^2) + z
Similarly:
delta_tower2_z = sqrt(DELTA_DIAGONAL_ROD^2 - (delta_tower2_x - x)^2 - (delta_tower2_y - y)^2) + z
delta_tower3_z = sqrt(DELTA_DIAGONAL_ROD^2 - (delta_tower3_x - x)^2 - (delta_tower3_y - y)^2) + z
Once the delta heights for four links are calculated, it is only a matter of asking the stepper motors to move the carriages to those heights:
planner.buffer_line(delta_tower1_z, delta_tower2_z, delta_tower3_z, target[E_AXIS], feedrate_mm_s, active_extruder);

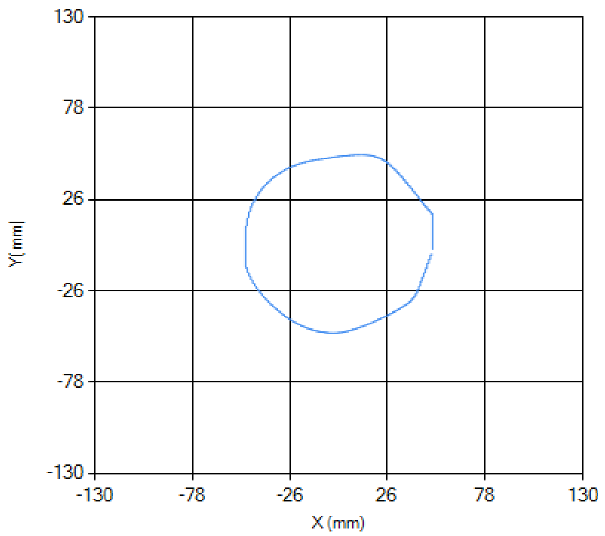

Figure 5. Coupler curve formation in existing design

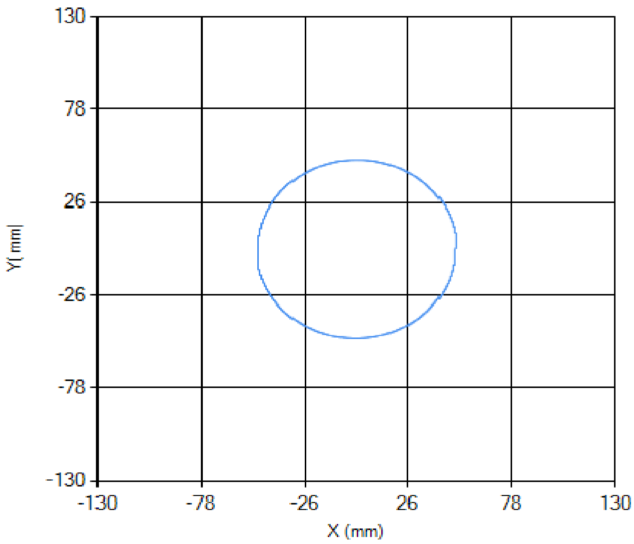

Figure 6. Coupler curve formation on new design

By proper calibration the printing quality, surface finishing and accuracy can be increased greatly through variation in angles for each links, and the chances of failure can be reduced to the minimum amount through coupler curve formation as like in Figure 6 than Figure 5. The only numbers that really matter are the distances in the XY plane from each carriage to the effector perimeter.

C. Static and Dynamic Analysis of Existing and New Model

Dynamic analysis is the testing and evaluation of an application during runtime. Static balancing also called gravity compensation which is important, if the forces/torques exerted by joint actuators are reduced, the full potential of machine will be improved. Static analysis is the testing and evaluation of an application by examining the code without executing the application. If one chooses to emulate the zero-free-length behaviour, for instance with a pulley and string arrangement or other mechanical in future, then some mechanical complexity is added to the system, as well as some friction.

Figure 7 shows the decreasing of curve formation in means of jerks on various angles for the third link in the existing model whereas, the position of jerks in fourth link is shown in Figure 8.

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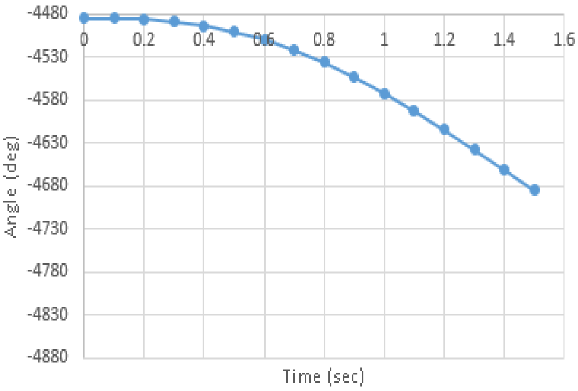

Figure 7. Position for jerk on three links

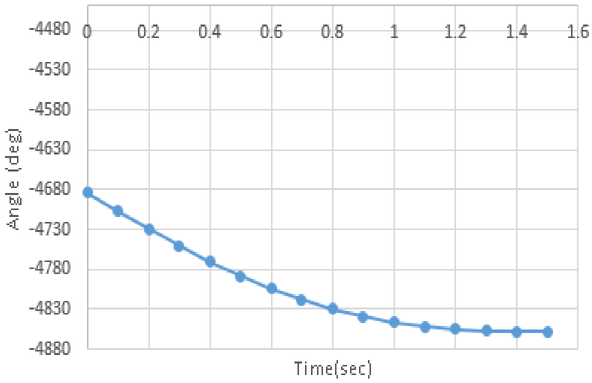

Figure 8. Position for jerk on four links

The acceleration of the movement in the end effector shows decreasing of curve formation and then increases gradually in a sinusoidal wave formation on both the links as shown in Figure 9 and Figure 10 in 0.1 sec.

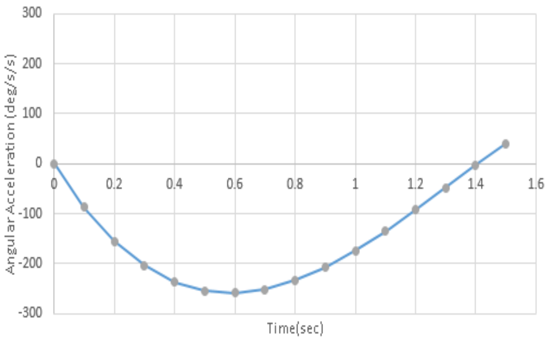

Figure 9. Acceleration on three the links

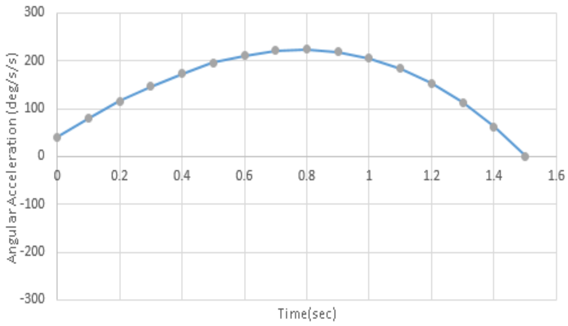

Figure 10. Acceleration on four the links

The velocity of the movement in the end effector shows in a sinusoidal wave formation on both the links as like in the acceleration curve in Figure 11 and Figure 12 respectively.

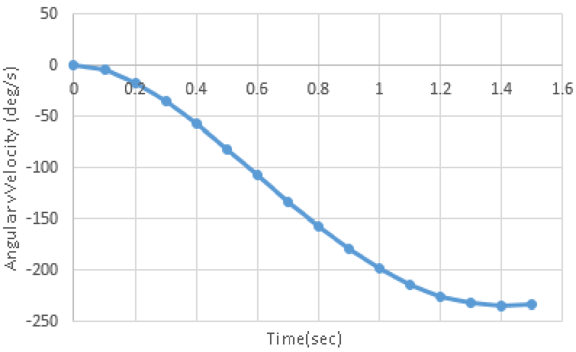

Figure 11. Velocity progression- three links

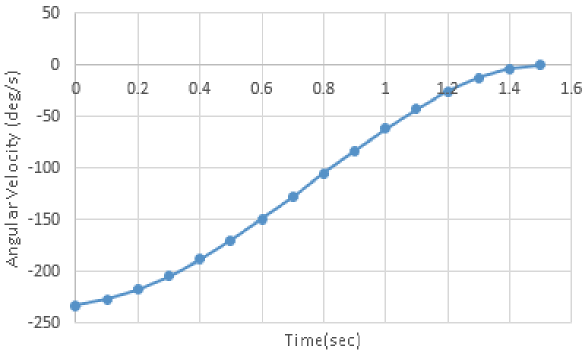

Figure 12. Velocity progression- four links

Further the jerk obtained at the movement in the end effector shows trajectory path of curve formation on both the links as like in the acceleration curve. The Combination of both existing links and new added links has been compared with the form of inverse kinematics and obtains a slight variation in finishing one complete layer through jerk obtained when compared to existing one as shown in Figure 13 and Figure 14.

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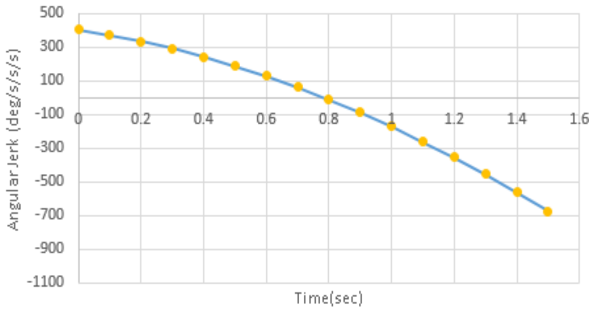

Figure 13. Jerks in three links

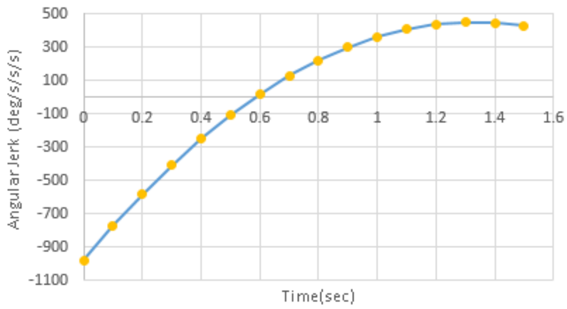

Figure 14. Jerks in four links

In the meanwhile for the static analysis, the stress attained at the end effector shows deformation due to force applied as shown in Figure 15 for the three links and Figure 16 for the fourth links.

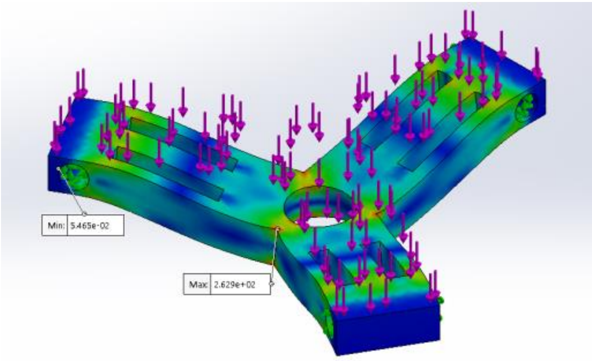

Figure 15. Stress on third link end effector

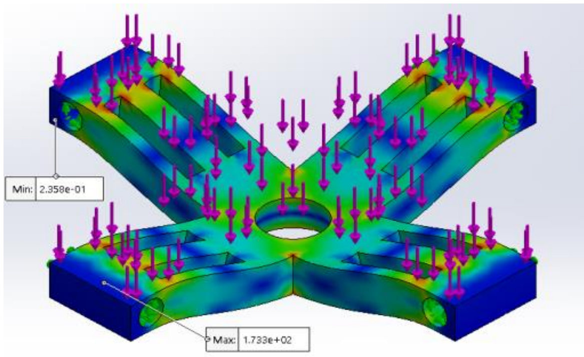

Figure 16. Stress on fourth link end effector

The strain analysis checked at the end effector shows elongation due to the same force applied as like in static analysis which is shown in Figure 17 for the three links and Figure 18 for the fourth links.

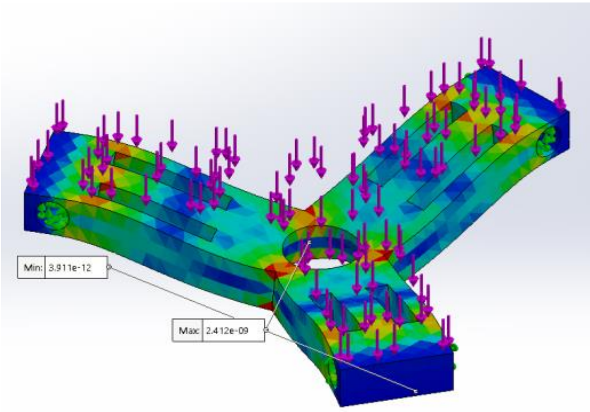

Figure 17. Strain on third link end effector

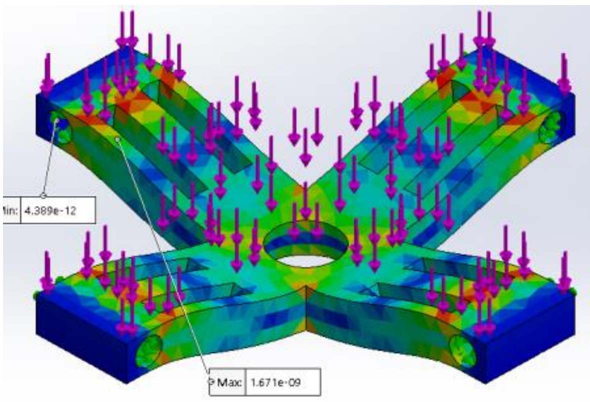

Figure 18. Strain on fourth link end effector

The displacement obtained due to strain is also analysed at the end effector shows the deflection in mm for both maximum and minimum forces applied for the links in Figure 19 and Figure 20.

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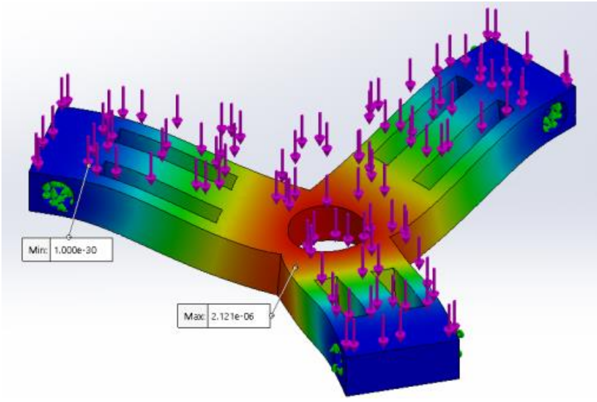

Figure 19. Displacement on third link

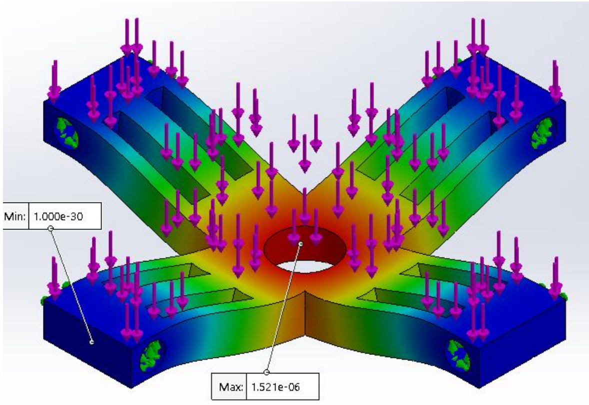

Figure 20. Displacement on fourth link

The primary advantage of static analysis: It examines all possible execution paths and variable values of the delta type end effectors, not just those invoked during execution. Thus static analysis can reveal errors that may not manifest themselves until weeks, months or years after release. In this delta type 3D printer we can also print the object without using the hot bed. Which is also a difference with the existing delta 3D printer used for the filaments like Polylactic Acid (PLA). This aspect of static analysis is especially valuable in security assurance of the model, because security attacks often exercise an application in unforeseen and untested ways in 3D printing.

D. Results and Discussion

The outcome of this project is to introduce a new link along with the existing three links of Delta printer which has been successfully completed. The material selection of the various elements is economical which has been modelled using CAD software- Solid works. Similarly, the Coupler curve formation in means of MATLAB is been analyzed, where Table 1 shows the printing area that attains a circular resolution in Fig 6 without a polygon formation as in Figure 5.

TABLE 1 Circular curve on the edge of workspace

Velocity (mm/s)	Time (s)	Force for 3-Links (N)	Force for 4-Links (N)
113	2.567	2.947	0.5
	2.943	2.538	1
	1.511	1.621	1.5
	1.205	1.204	2
	1.293	1.321	2.5
	1.873	1.253	3

The Static and Dynamic balancing is a classic problem in the theory of machines and mechanisms. Here the Static and Dynamic formation of the kinematics mechanism is analysed with comparison between the existing three pairs and the newly added pair through the Solid works simulation in means of velocity, acceleration, jerk, stress, strain and displacements of the forces applied. Two of the links moves in-plane and the third rotates out of the projected plane.

Table 2 compares the acceleration between both the links with small variation of 0.1 to 0.2 N in means of the movement in the end effector.

TABLE 2 Acceleration on third and fourth axis

Acceleration (m/s^2)	Time (s)	Force for 3-Links (N)	Force for 4-Links (N)
2.4	0	1.751	1.834
	0.5	2.197	2.207
	1	2.071	2.138
	1.5	1.831	1.941
	2	1.685	1.734
	2.5	1.553	1.621

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Table 3 compares the velocity between both the links with small variation for the Lissajous curve movement.

TABLE 3 Lissajous curve on X-Y plane

Velocity (mm/s)	Time (s)	Force for 3-Links (N)	Force for 4-Links (N)
200	0	1.853	1.874
	0.5	1.897	1.917
	1	2.001	2.138
	1.5	2.251	2.281
	2	2.685	2.634
	2.5	3.783	3.861

The addition of fourth link is studied and analysed with benefits of the errors with directional accuracy in Table 4, where final experimental accuracies obtains with 99% confidence graphically. But the printing accuracy of CDPP can be expressed more intuitively by comparing the physical and CAD model parameters.

TABLE 4 Errors on velocity and acceleration at end effector

Idle State Accuracy for both the links	Three Link Directional Accuracy	Four Link Directional Accuracy
±0.160 mm	±0.476 mm	±0.282 mm

Finally, a corresponding geometric error comparison simulations is checked out and further the linear-array printing experiments are to be carried out to verify the optimization algorithm for future works. Table 5 obtains the stress comparison between both the links with constant time calculation which shows variation in loads.

TABLE 5 Comparison of stress analysis

Time (s)	Stress on 3-Links (N/m^2)	Stress on 4-Links (N/m^2)
1	2.629	1.733
2	2.41	1.588
3	2.191	1.444
4	1.972	1.3
5	1.753	1.156
6	1.534	1.012
7	1.315	8.674
8	1.096	7.233
9	8.768	5.791
10	6.577	4.349
11	4.387	2.907
12	2.196	1.465
13	5.465	2.358

The strain comparison between both the links with constant time calculation obtains slight elongation in very small distance as like in Table 6.

TABLE 6 Comparison of strain analysis

Time (s)	Strain on 3-Links (mm/s)	Strain on 4-Links (mm/s)
1	2.412	1.671
2	2.212	1.532
3	2.011	1.393
4	1.81	1.254
5	1.61	1.115
6	1.409	9.766
7	1.208	8.377
8	1.007	6.988
9	8.067	5.599

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The displacement attained between both the links with the elongation obtains point to point changes through strain which is shown in Table 7.

TABLE 7 Comparison of strain analysis

Time (s)	Displacement on 3-Links (mm)	Displacement on 4-Links (mm)
1	2.121	1.521
2	1.945	1.394
3	1.768	1.268
4	1.591	1.141
5	1.414	1.014
6	1.237	8.873
7	1.061	7.605
8	8.839	6.338
9	7.071	5.07
10	5.303	3.803
11	3.536	2.535
12	1.768	1.268
13	1	1

IV. CONCLUSION

The quantity and quality of the work is certainly impressive, with suitable design which is being developed a long side for 3D printer parts, to fit the extra axis. As of now, we can do the calculation of traverse for fourth link, but once the work has been presented, all the necessary files will be made public. We can see versions of the hardware finding their way onto printers other than the existing delta model, and we can see this becoming another piece of the regular armory available to those of us who make new products.

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