FABRICATION AND OPTIMIZATION OF DELTA COORDINATE - FUSED DEPOSITION MODELLING MACHINE

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Abstract: 3D printing is one of the better ways to achieve customized manufacturing. 3D printing has widespread applications starting from making a product in an industry to printing a cake in a bakery, even body parts like prosthetic ears, implants. Fused Deposition Modelling (FDM) is gaining distinct advantages in manufacturing industries, because of its ability to manufacture parts with complex shapes without any tooling requirement and less human interface. There are many types of Fused Deposition Modelling printers available according to coordinate system they use. The printers adopt Cartesian, polar or Delta coordinate system in principle. Though, the Cartesian printers are having advantages but slow as compared to Delta printers. The objective of this project is to fabricate and optimization of process parameters for Delta Coordinate Fused Deposition Modelling Machine.

Keywords: **3D Printing, Delta coordinate system, Fused Deposition Modelling.**

1. Introduction:

In late 1980, the first 3D printing technology (additive manufacturing) was evolved which was known as rapid prototyping. This is first invented by CHARLES HULL. This was developed for usage any of the product as prototype, it is very cost effective to develop in industry. The 3D systems' printing was introduced in 1987, which was tested and sold which was made by SLA (stereo lithography apparatus). Within the same year there was another printing machine which used the other technique, which was SLS (SELECTIVE LASER SINTERING). The Additive Manufacturing (AM) process of slicing 3D model, then printing the slices, and the property of material used to combine it forms a 3D model. It's just a 2d printer adding layer upon layer coined the name additive manufacturing or 3D printing. 3D printers are customized prototyping machines suitable to work at any place.

Fig.1. Process done in additive manufacturing.

2. Types of Additive Manufacturing:

Additive Manufacturing (AM), commonly known as 3D printing, can be defined as the "joining of materials to make an object from 3D model data, generally layer upon layer, as opposed to formative manufacturing methodologies" in the International Organization for Standardization (ISO)/American Society for Testing and Materials(ASTM) 52900:2015 standard [1]. Based on the standard, AM processes can be classified into seven categories: Binder Jetting, Material Extrusion, Powder Bed Fusion, Directed Energy Deposition, Material Jetting, Sheet Lamination and Vat Photopolymerization as shown in Fig.2.

Fig.2. Types of printing technologies

2.1 Binder Jetting:

The binder jetting printer uses two different materials; one is a powder based material and the other is a binder. Being a binder it acts as an adhesive between powder layers. The build material is in amorphous and the binder is in liquid form. The printing process consists of laying of either bronze or stainless steel or Inconel powder and then the print head moves across it to selectively spray binder solution to obtain a particular geometry of the object. Then the heating lamp dries the layer. Subsequently a fresh layer of powder is rolled over it, and the process repeats. Once the above process is over the object is then placed in an oven for curing.

2.2 Directed Energy Deposition:

Directed Energy Deposition (DED) is suitable for producing metal parts through the layer upon layer deposition of molten metal powders or filament. It employs energy-intensive source either a laser or an electron beam to generate a melt pool on the substrate into which metal powder or filament is injected. The molten pool follows a specified route and fills the top of substrate [2]. The molten pool is progressively built up as per the designed CAD geometry, where it solidifies. Directed Energy Deposition (DED) covers various range of methods such as Laser Metal Deposition (LMD), Laser Engineering Net Shaping (LENS), Direct Metal Deposition (DMD), Direct Laser Deposition (DLD), Directed Light Fabrication (DLF), laser consolidation, 3D laser cladding, laser deposition welding and powder fusion welding, many of which are trademarks of several "machine manufacturers or research establishments".

2.3 Material Extrusion:

Most common consumer grade additive manufacturing. The material comes in filament form and is fused and deposited on the space of the building plate. The 3D printer builds an object, layer by layer, by melting a material from a computer controlled nozzle. Materials used in material extrusion process are polycarbonate (PC), acrylonitrile butadiene styrene (ABS), polylactic acid or polylactide (PLA), polyphenylsulfone (PPSF), PC-ABS blends, and PC-ISO [3]. The names available in the literature for the material extrusion process are Fused Filament Modelling (FFM), Fused Filament Fabrication (FFF), Melted and Extruded Modelling (MEM) and Fused Deposition Method (FDM).

2.4 Material Jetting:

Material Jetting is one of the standard additive manufacturing technologies that has scope and design pattern suitable for the desktop version of 3D printers as industrial 3D printers. The technology fabricates a 3D part just like an inkjet printer prints a two-dimensional image [4]. A typical apparatus for material jetting has printer head consisting of two nozzles and an UV source. One nozzle is used to supply the building material while another is used for the support material. The printer head deposits a computer controlled pattern of building material as well as support material layer upon layer, while the UV source directs radiation towards the immediately deposited material droplet to solidify it with the adjacent droplet. Once the model is finished, it is allowed to cool and hardened. The support material is not the part of the model but is usually deposited along the building material to keep the model in fixed orientation while it is printed. Later on, Support material can be removed using a sodium hydroxide solution or water jet. The term "Drop on Demand (DOD)" is used for referring the drop by drop wise fabrication of model in the technology's context. The synonyms of Material Jetting are Multi-jet modelling, Drop On Demand (DOD), Thermojet and Polyjet printing.

2.5 Powder Bed Fusion:

Powder bed fusion (PBF) method use either a laser or electron beam to melt and fuse powder material together. All Powder bed fusion process involves the spreading of the powder material over previous layers [5]. According ASTM standards the alternative names for Powder Bed Fusion may be listed as, Selective Laser Sintering (SLS), Direct Metal Laser Sintering (DMLS), Selective Laser Melting (SLM), Electron Beam Melting (EBM), and Selective Heat Sintering (SHS). But there exist differences in printing processes. Electron beam melting method requires a vacuum but can be used with metals and alloys in the creation of functional parts.

2.6 Sheet Lamination:

Sheet Lamination Printing is an additive manufacturing method in which sheets of material are bonded to form a 3D model. The sheets of building material are cut through laser or knife and then joined by using either an adhesive or by wielding to form a 3D object. The process is also called ultrasonic additive manufacturing (UAM) or Ultrasonic Consolidation (UC), in which the building material is metal sheet. But as per the researches available, if paper is used for making the 3D object then it is known by the name Laminated Object Manufacturing (LOM).

2.7 Vat Photopolymerization:

Vat photopolymerisation method has a container filled with photopolymer resin liquid, out of which the model is constructed layer upon layer. An ultraviolet (UV) light source is used to cure or harden the resin where required, platform moves downwards after each new layer is cured. According ASTM standards the alternative names for Vat Photopolymerisation may be listed as Stereo lithography Apparatus (SLA), Digital Light Processing (DLP), Scan, Spin, and Selectively Photo cure (3SP), Continuous Liquid Interface Production (CLIP). But there exist differences in processes.

3. Fused Deposition Modelling-FDM:

The technology was developed and patented in 1980's by S. Crump. Later, Crump started a company - Stratasys in 1988 which trademarked the term "Fused Deposition Modelling" [6]. Fuse deposition modelling (FDM) is a material extrusion process in which material is drawn from extruder through a nozzle, where it is heated and is then deposited layer upon layer. The extruder can move horizontally and a platform moves up and down vertically after each new layer is deposited. The disadvantage of the FDM technique is the ineffectiveness of the system to produce part quickly as that of other technology. The build time for a given print can be reduced by positively decreasing the layer thickness and negatively reducing the infill density.
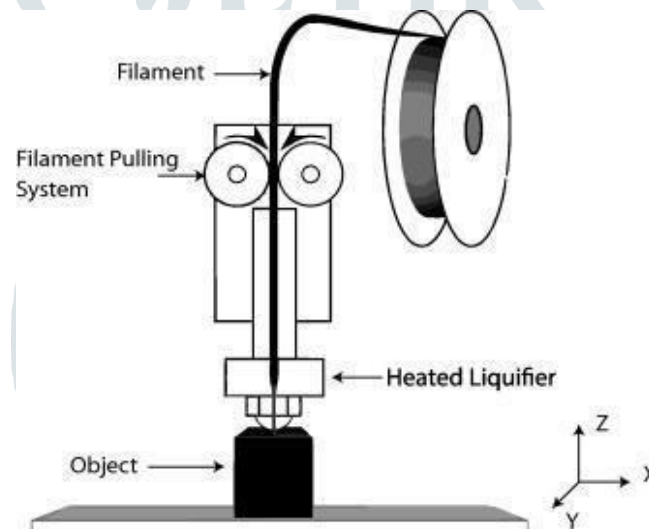

Fig.3. Schematic diagram of FDM

4. Types of FDM 3D printers:

There are several types of FDM 3d printers available according to coordinate system [7]. They are Cartesian, polar and Delta coordinate system printers.

          1. Cartesian 3D printer   **2. Delta 3D printer**

Fig.4. FDM Printers

5. Introduction to Delta Printer:

A delta printer is in fact a parallel robot and has been used in 3D printing by fused deposition modeling (FDM) [8]. The delta coordinate systems normally used by pick and place robots in industries, this result in a fast and accurate positioning. Delta configuration has three legged mechanism to reach a circular workspace in a plane. Total work space look as a Cylinder. Delta configuration came around 2005 having principles adopted from industry level bots, first delta printer is developed by Kossel. This is a good move towards large volume and easy build printers. It's also same concept of tri linearization as all three moving axial rods concentrate to reach a point. Best part about delta coordinate printer is that it just needs very small movement when compared with others. This uses three linear axes, where a joining end results in reaching each point of the circular work space in a plane. Three linear axes are kept at each vertex of triangle.

5.1 Why Delta?

It very easy to work with Cartesian coordinates, it feels easy to imagine in with. Every cad software also stores same format to store them to a file. They are many types of 3D printers available according to coordinate system they use, generally Cartesian, polar and Delta coordinate system printers. Cartesian printers are the most used among them, as they are easily conceptualizing for makers. Now let's talk about what it lags, it is comparatively slow as compared with delta. Here are some points which reasons are behind to choose delta printer.

- ❖ **EASY** to build than Cartesian.
- ❖ **FAST** than Cartesian, moving from point to point.
- ❖ **3 Steppers** are enough for complete movement, even same load on each stepper.
- ❖ **NO** need of **moving print bed**, many printers do it this which makes print to deform to another shape.
- ❖ **REDUCED** parts which results in low maintenance.
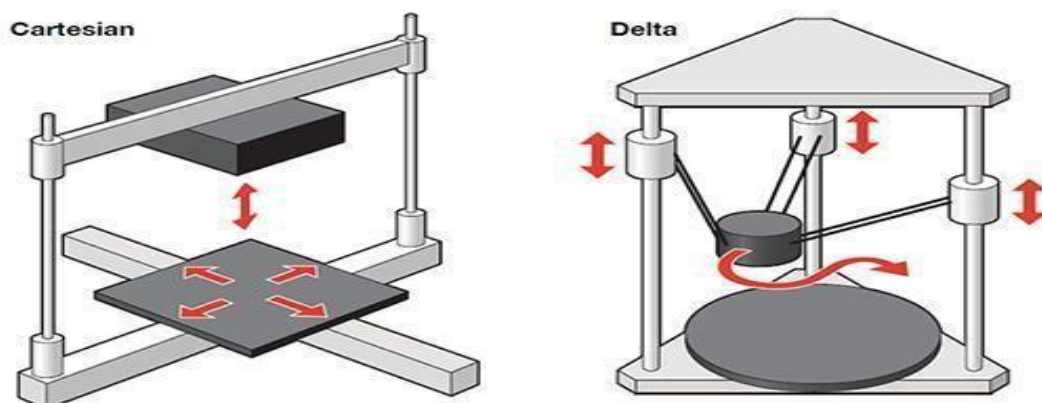- ❖ **TALL** built volume.

Fig.5. Working of Cartesian and Delta Printers

6. Delta Printer Kinematics:

Reverse kinematics has been used to derive the equations to the printer and the goal is to map each Cartesian point to the motion of three motors, and then made the motion onto centre extruder portion. To find the relation between Cartesian and parallel rod movements, some constants have been taken to figure out the location of the required points. Firstly, the values from G-codes are taken, which then printed using a delta printer. The main objective is to find the motion of stepper motors started by making a coordinate system on the printer base and assumed that three pairs of rods parallel to each other. A delta structure has

three vertical axes, each axis has a carriage that can slide along the vertical sliding guide. A carriage and the platform are connected using a pair of parallel rods [9]. All three pairs of rods are arranged with a phase difference of 120 degrees. Rods are at 90˚, 210˚ and 330˚.
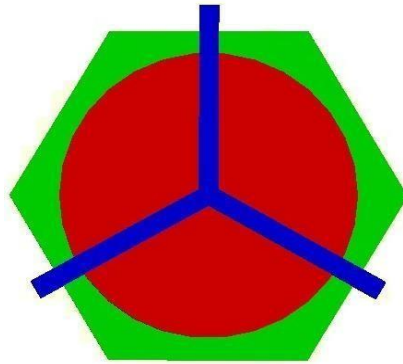

Fig.6. Axis of Delta printer

In the above picture blue line gives the position of rods to be placed, which is at the end of it. Now the arrangement of rods is done.

7. Assembly of the Printer:

The control unit of a delta structure consists of an Arduino Mega 2560 microcontroller board, LCD and SD card panel that plugs into RAMPS (RepRap Arduino Mega Pololu Shield) board and four high torque hybrid stepper motors. The whole system is controlled and communicated by an Arduino chip. The mechanical parts used for this printer are Steel bars of length 70cm and sides 12mm and 20cmm in length, linear bearings to fit steel rods, arm rods with ball joints, aluminium GT2 pulleys for stepper motors, mechanical end stops, linear bearing for feeder motor, screws, nuts and bolts. The electrical parts include Arduino Mega 2560 microcontroller board, RAMPS 1.4 electronic board that sits over mega, LCD and SD card panel that plugs into RAMPS, 100k thermistor, cables of good quality.

Fig.7. Assembly of the printer

7.1 Software Used:

The Slic3r is a simple to use host software, which is be compatible with most firmware around. That can add STL files and slice them all together. Just call "Slice & Load" and the job gets delegated to the current slicer, showing its output in the log window. In the G-Code editor change or analyse of code can be done. The software is compatible for Windows XP or higher, Linux, and Mac OS X.

7.2 Material Used:

The different materials for additive manufacturing can be used based on the needs of market, depending on the application. Polylactide or Polylactic acid (PLA) is one of the most popular materials for consumer grade additive manufacturing. PLA is a thermoplastic polymer that is derived from renewable resources, more specifically from corn starch or sugar cane. This property sets aside from other commonly used plastics, which are procured through the distillation and polymerization of non-renewable petroleum reserves. PLA filament being a biodegradable product, tends to naturally break down in about three to six

months. Other thermoplastic materials can take up thousands of years to decompose. For PLA material the nozzle temperature should be around 210^0 C with bed temperature around 60^0 C.
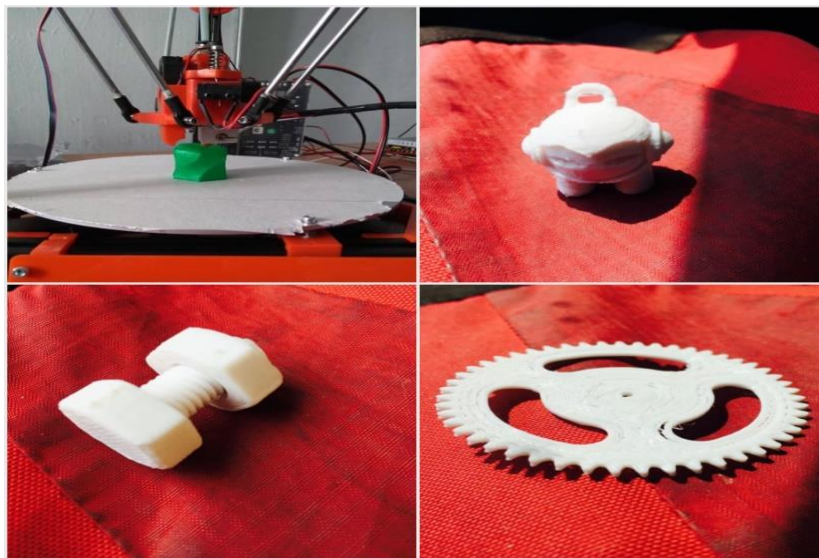

Fig.8. Parts fabricated by delta printer.

7.3 Taguchi's Method:

Taguchi Technique is applied to plan the experiments. The Taguchi method has become a powerful tool for increasing productivity during research and development, so that good quality products can be manufactured quickly and at low cost. Dr.Taguchi developed a process based on" ORTHOGONAL ARRAY" experiments which gives much reduced variance for the experiment with optimal control parameters. Thus the Design of Experiments with optimization of control parameters to obtain best results is achieved in the Taguchi Method. "Orthogonal Arrays" provide a set of well-balanced experiments.

Table 1. Orthogonal factor level table for Delta Coordinate FDM.

Levels	Printing Speed(mm/s) (A)	Layer Thickness(mm) (B)	Filling Ratio (%) (D)
1	40	0.15	20
2	60	0.20	40
3	80	0.25	60

Table 2. L_9 orthogonal array design for Delta Coordinate FDM.

SL.NO	FACTORS		
	A	B	D
1	40	0.25	20
2	40	0.20	40
3	40	0.15	60

4	60	0.20	20
5	60	0.15	40
6	60	0.25	60
7	80	0.15	20
8	80	0.25	40
9	80	0.20	60

L_9 orthogonal array is selected to improve experimental efficiency [10]. The build time, surface finish and dimensional height tests were conducted on the printed specimens of size 40mm*30mm*20mm by using the optimized processing parameters.

Fig.9. Printed specimens.

8. Results and Discussions:

Table 3. Optimization table with Taguchi method

Sl. No	Build Time	Comparability Sequence	Accurate dimension height	Correction Factor	Average of Correction Factor
1	26	0.68	20.04	0.99	0.83
2	37	0.97	19.9	0.992	0.981
3	38	1	20.01	0.997	0.998
4	25	0.65	20.02	0.998	0.824

5	28	0.73	19.95	0.994	0.862
6	35	0.92	20.03	0.998	0.959
7	22	0.57	19.98	0.996	0.783
8	27	0.71	20.06	1	0.855
9	34	0.89	20.02	0.998	0.944

In above L9 orthogonal array indicates that optimization results in which the L7 has the lowest a time consumption and minimum dimensional errors with 78% of Correction Factor.
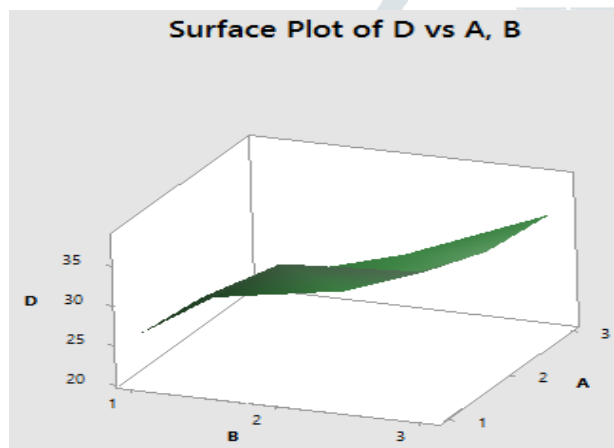
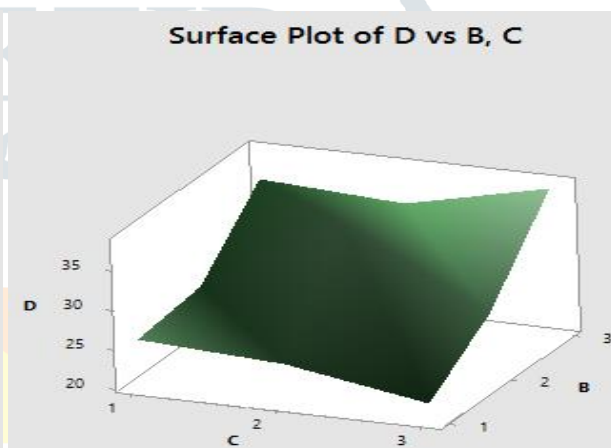**8.1 Surface Plot of output vs inputs:**

Fig.10. Surface Plot of output vs inputs (A, C)

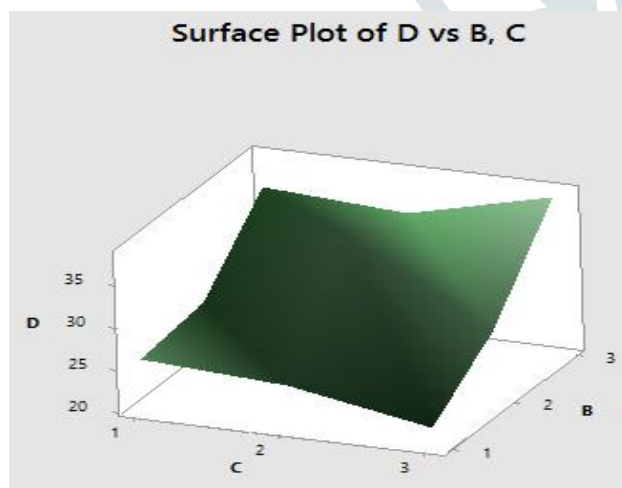Fig.11. Surface Plot of output vs input (B, C)
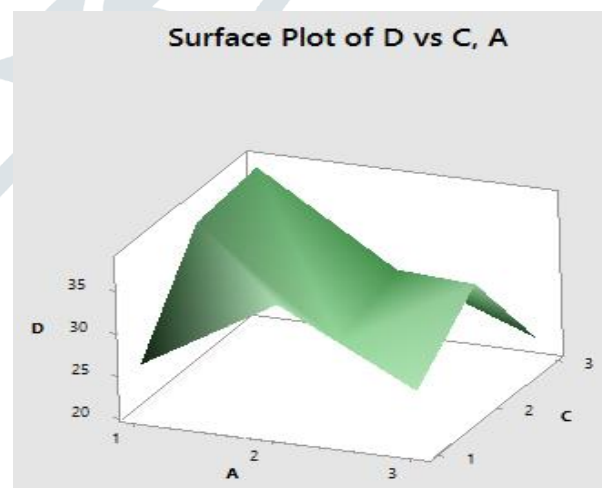

Fig.12. Surface Plot of output vs input (B, C)

Fig.13. Surface Plot of output vs input (C, A)
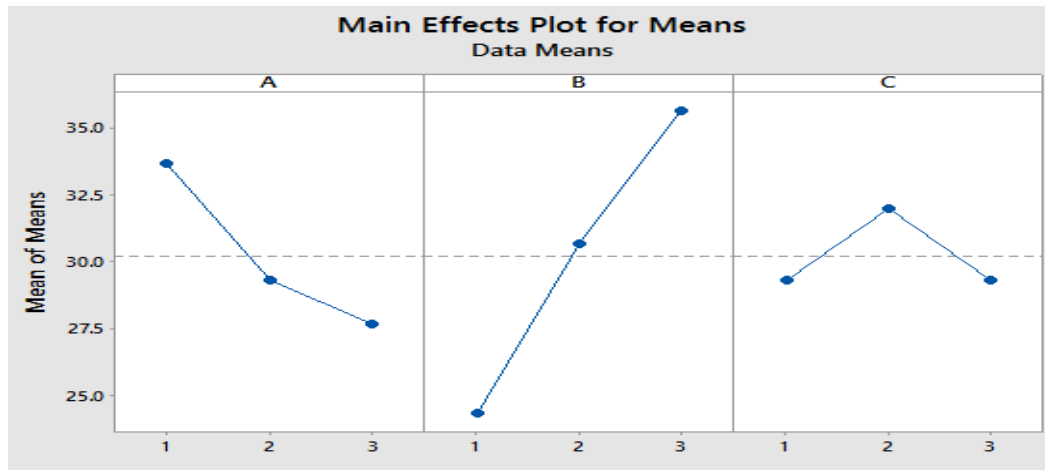
8.2 Main Effects Plot for Means:

Fig.14. Main Effects Plot for Means

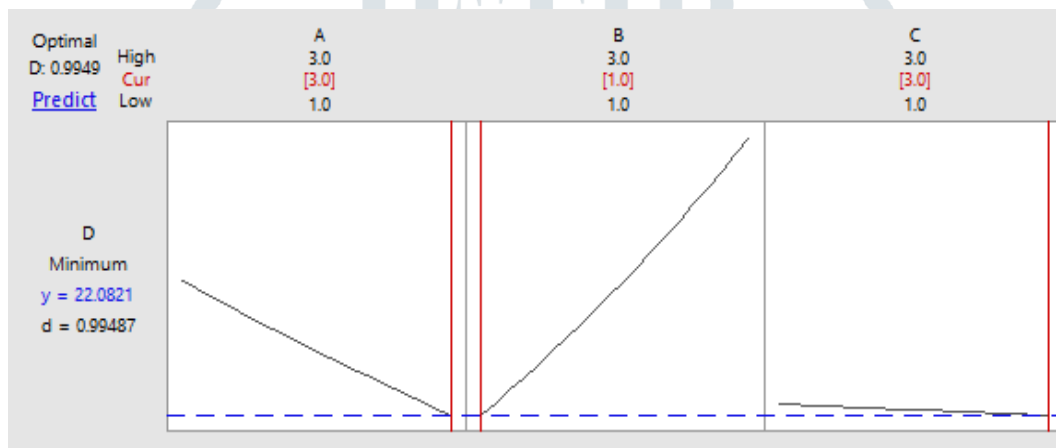**8.3 Main Effects Plot for outputs:**

Fig.15. Main Effects Plot for outputs

9. Conclusions:

In this project the functionality of full-fledged commercial 3D printers are considered. The main objective is to reduce the cost of printer. This research in finding the best structure has enriched the knowledge about them. In this the conclusion has made that delta structure is a better one to choose. From knowledge about the complexity of its kinematics, and hard work has resulted in converting the concepts to code and then to a working model, also added another feature to the printer to calibrate in seconds. By using delta configurations which succeeded in producing the printer around Rs.15000. The build time, surface finish and dimensional height tests were conducted on the printed specimens of size 40mm*30mm*20mm by using the optimized processing parameters. The L_9 orthogonal array indicates that optimization results in which the L_7 has the lowest time consumption and minimum dimensional errors with 78% of Correction Factor (C.F).

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