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DESIGN AND DEVELOPMENT OF A LINEAR DELTA 3D PRINTER

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Abstract: *The paper presents the design process and the development of a linear Delta 3D printer. The most commonly used mechanical structure for Fused Deposition Molding (FDM) printers is based on the traditional parallel mechanism. This paper highlights the advantages of a Delta structure 3D printer in comparison with the Cartesian structures regarding various technical specifications such as accuracy, printing speed, layer thickness and the overall printer's size. AHP Instruments were used to identify the optimal design of the printer and a Pugh matrix was devised to obtain the best ranking of the possible 3D printing structures. The developed printer's accuracy has been compared with other market available Cartesian structure printers to highlight the accuracy paired with printing speed of the Delta 3D printer.*
Key words: *3D printer, additive manufacturing, design, AHP*

1. INTRODUCTION

Additive manufacturing (AM), commonly known as 3D printing, has been available commercially in the last 30 years. Still, the early prototypes were expensive. Thus, the widespread adoption of 3D printers has only happened after 2000 due to RepRap Project and other similar initiatives as well as the fact that the significant AM patents expired [1].

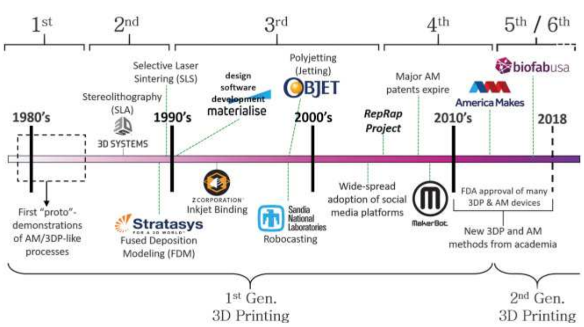

Fig. 1. *The 3D printer development timeline in regards to the essential AM patents expire* [1]

The first 3D printer patent was published in Google Patents in 1986 under the name of an Apparatus used to produce three-dimensional objects by stereo-lithography. The first 3D printer concept was developed by one of the co-founders of 3D Systems Company, one of the leading companies in the 3D printers' market, which also extends towards 3D scanning and software development.

The global market for 3D printing market has rapidly evolved, and the attention has swapped from hobbyists towards various industries such as aerospace, automotive, electronics. The overall Additive Manufacturing market is projected to reach $16 billion industry in 2020 and over $40 billion in the following five years as it is presented in Statista [2].

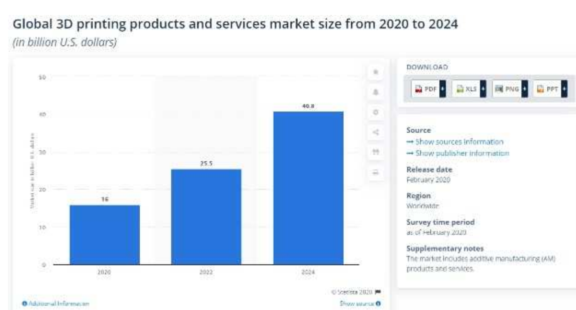

Fig. 2. *3D Printing products and service market size prediction 2020-2024 [2]*

The increase market size of additive manufacturing has led some specialists to consider that this technology will be at the basis of the Fourth Industrial Revolution.

The most common 3D printing technologies on the market are the following:

- FDM – Fused Deposition Modeling
- SLA – Stereolithography
- DLP – Digital Light Processing
- SLS – Selective Laser Sintering
- SLM – Selective Laser Melting
- 3DP – Inkjet Tridimensional Printing
- LOM – Laminated Object Manufacturing
- PJP – PolyJet Printing

FDM type 3D printers are the most common, because the technology behind them is very accessible. These printers come in different shapes and sizes, with a variety of configurations, from the classic extruder (1-2 or more extruders, grouped or individual) to multi-tools (printing, laser engraving, CNC carving).
The classification of 3D printers can be done in several ways, but the most common classification is related to their structure. Depending on their mechanical structure there are:

- Cartesian structure (Cartesian coordinates)
- Delta structure
- Polar structure (Polar coordinates)
- Scara structure

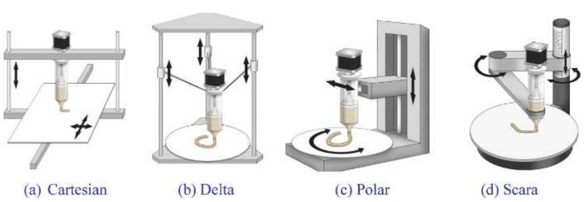

Fig. 3. *3D Printer structure types [3]*

The 3D printer described in this paper is based on the linear delta structure, Kossel type (open source).

2. DESIGN REQUIREMENTS

The methodology for showcasing the differences between some of the most widely used 3D printing machine structures and their compliances regarding their performance expectations consist in mainly three phases:
Firstly, the challenge was to identify some of the key specifications that define how 3D printers are required to perform. For this endeavor the authors consulted the specialty literature and extracted 10 main specifications [4][5][6][7]:

- Printing speed (min. 100 mm/s);
- Accuracy (50 microns ±10);
- Printing volume (min. 250x220 mm);
- Layer thickness (100 microns ±10);
- Noise (55 db ±5);
- Printer's size (max. 750x450 mm);
- Printer's mechanism (delta);
- Printer's source file ext. (.stl);
- Number of material colors (min. 1);
- Printing cost (max. 20 €/kg).

Secondly, the identified specifications were ranked using a widely employed instrument (AHP – Analytical Hierarchy Process), that prioritizes items, when they can't be numerically compared and there are no objective criteria that can be used to compared them.

Group: Top Level ITEMS — Output — Completed:

AHP Toplevel Matrix

9	9,00	an order of magnitude more important
8	8,00	absolutely more important (8x as important)
7	7,00	demonstrated more important
6	6,00	demonstrated more important (6x as important)
5	5,00	essentially more important
4	4,00	essentially more important (4x as important)
3	3,00	considerably more important
2	2,00	twice as important
1.5	1,50	somewhat more important
1	1,00	Equally important
0.67	0,67	somewhat less important
0.5	0,50	half as important
0.33	0,33	clearly less important
0.25	0,25	essentially less important (other item 4x as important)
0.2	0,20	essentially less important
0.17	0,17	demonstrated less important (other item 6x as impo...
0.14	0,14	demonstrated less important
0.12	0,13	absolutely less important (other item 8x as important)
0.11	0,11	an order of magnitude less important

Input	1 Printing speed (min. 100 mm/s)	2 Accuracy (50 microns ±10)	3 Printing volume (min. 250x220 mm)	4 Layer thickness (100 microns ±10)	5 Noise (55 db ±5)	6 Printer's size (max. 750x450 mm)	7 Printer's mechanism (delta)	8 Printer's source file ext. (.stl)	9 Number of colors (min. 1)	10 Printing cost (max. 20 €/kg)	Importance in group
1 Printing speed (min. 100 mm/s)		0.2	0.33	0.33	5	3	0.33	3	5	3	7,2%
2 Accuracy (50 microns ±10)			4	0.5	7	6	4	5	8	4	24,5%
3 Printing volume (min. 250x220 mm)				0.33	6	2	0.2	3	4	3	8,4%
4 Layer thickness (100 microns ±10)					8	8	0.2	9	7	5	19,0%
5 Noise (55 db ±5)						2	0.14	2	3	0.2	2,8%
6 Printer's size (max. 750x450 mm)							0.17	4	4	0.5	3,4%
7 Printer's mechanism (delta)								8	9	8	25,6%
8 Printer's source file ext. (.stl)									0.2	0.5	1,9%
9 Number of colors (min. 1)										0.2	2,2%
10 Printing cost (max. 20 €/kg)											4,9%

Fig. 4. *AHP – Delta Printer*

Instead, this technique uses successive pairwise comparison between items (by devising an MxM matrix) to employ local objectification, enabling finally the expression of the importance of each item in the list, in percentage. It should be noted that by not comparing all the elements at once errors can be included in the matrix. However, for overcoming this drawback that authors also calculated the so called "consistency ratio" (CR). The specialty literature argues that a CR value less than or equal to 0.1 is deemed acceptable [8]. In our case the CR value was 0.073.

	CR Value =	0.073	OK								
	Pairwise comparisons										
Item Number	Item Number	1	2	3	4	5	6	7	8	9	10
	Item Description	Printing spee	Accuracy (50	Printing volum	Layer thickne	Noise (55 db	Printer's size	Printer's mec	Printer's sour	Number of co	Printing
1	Printing speed (min. 100 mm/s)	1.00	0.20	0.33	0.33	5.00	3.00	0.33	3.00	5.00	3.00
2	Accuracy (50 microns ±10)	5.00	1.00	4.00	0.50	7.00	6.00	4.00	5.00	8.00	4.00
3	Printing volume (min. 250x220 mm)	3.00	0.25	1.00	0.33	6.00	2.00	0.20	3.00	4.00	3.00
4	Layer thickness (100 microns ±10)	3.00	2.00	3.00	1.00	8.00	8.00	0.20	9.00	7.00	5.00
5	Noise (55 db ±5)	0.20	0.14	0.17	0.13	1.00	2.00	0.13	2.00	3.00	0.20
6	Printer's size (max. 750x450 mm)	0.33	0.17	0.50	0.13	0.50	1.00	0.17	4.00	4.00	0.50
7	Printer's mechanism (delta)	3.00	0.25	5.00	5.00	8.00	5.88	1.00	8.00	10.00	8.00
8	Printer's source file ext. (.stl)	0.33	0.20	0.33	0.11	0.50	0.25	0.13	1.00	0.20	0.50
9	Number of colors (min. 1)	0.20	0.13	0.25	0.14	0.33	0.25	0.10	5.00	1.00	0.20
10	Printing cost (max. 20 €/kg)	0.33	0.25	0.33	0.20	5.00	2.00	0.13	2.00	5.00	1.00
	Sum	16.40	4.58	14.92	7.87	41.33	30.38	6.38	42.00	47.20	25.40

Fig. 5. *Pairwise comparison between technical specifications*

Criteria / Printer types	1 Cartesian structure	2 Delta structure	3 Polar structure	Importance
1 Printing speed (min. 100 mm/s)	+	++	+	7,4%
2 Accuracy (50 microns ±10)	++	+	+	22,9%
3 Printing volume (min. 250x220 mm)	+	++	-	8,6%
4 Layer thickness (100 microns ±10)	++	+	+	20,0%
5 Noise (55 db ±5)	--	+	--	3,0%
6 Printer's size (max. 750x450 mm)	+	--	+	3,8%
7 Printer's mechanism (delta)	--	++	--	24,7%
8 Printer's source file ext. (.stl)	++	++	++	1,9%
9 Number of colors (min. 1)	++	++	++	2,5%
10 Printing cost (max. 20 €/kg)	+	++	+	5,2%
Positive Effects	8	9	7	
Negative Effects	2	1	3	
Neutral Effects	0	0	0	
Net Effect	6	8	4	
Positive Priorization	55,6%	65,6%	24,2%	
Negative Priorization	-27,7%	-3,8%	-30,6%	
Net Effect	27,9%	61,8%	-6,4%	

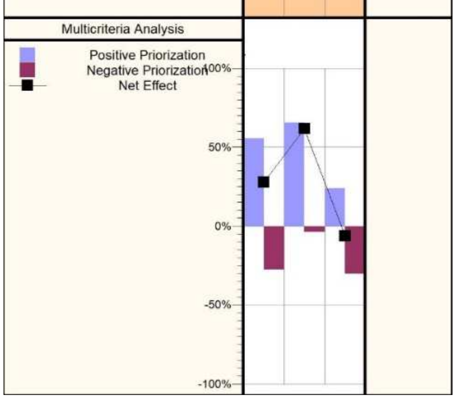

Fig. 6. *PUGH Matrix multicriteria analysis*

Finally, a Pugh matrix was devised, having as inputs the ranked performance specifications and the 3D printing machine structures.

This instrument can be deployed in various formats, the authors proposed a version that is more commonly used: the set of criteria (on the left) constitute the probing questions or, in our case, the performance specifications, and the concepts to be selected are the machine structures (on the top). A scale from -3 to +3 was selected for completing the matrix, with the following significance: -3 strong negative effect (used symbol --), -1 some negative effect (used symbol -), 0 neutral (used symbol 0), +1 some positive effect (used symbol +), +3 strong positive effect (used symbol ++). These values are multiplied with the importance factor of each item (specification). The multiplied values are then summed up and the "Net Effect" is obtained, representing the proportional rating of each 3D printing machine structure, using the following formula:

$$\sum_{i=1}^{n} = \frac{Importance\ of\ specification\ n}{100} \quad (1)$$
$$* \ machine\ structure\ score\ n$$

3. THE DESIGN AND DEVELOPMENT OF THE 3D PRINTER

Printer design begins with modeling independent subsystems:

- Linear motion system;
- Power supply mechanism
- Arm rods;
- Rod heads, joints;
- Frame structure.

These systems include both standardized elements and uniquely designed parts specially designed to ensure the interconnection of standard elements. The 3D modeling and kinematic simulation of the printer was performed in Catia V5.

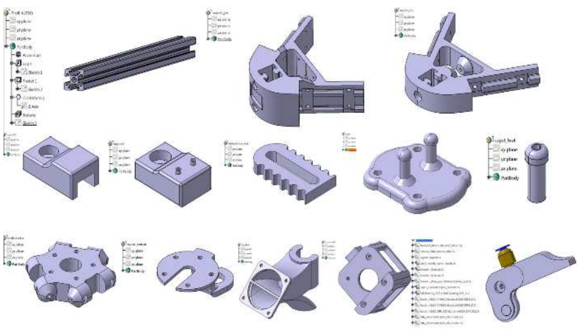

Fig. 7. *CAD components of the Delta printer*

The printer extruder is the subassembly that ensures the extrusion of the plastic filament (PLA, ABS, etc.). The designed extruder is similar to the one known on the market as Mk8, but has been modified to reduce the print head mass. Changes are made also in the area of wire extrusion area mainly on fixing the extrusion nozzle in the extruder body.
Having all the CAD models for the components and subassemblies, the 3D models were assembled (as seen in *Fig 9*) and simulated kinematically in Delmia V5 to check the workspace and possible collisions.

Fig. 9. *The digital assembly of the printer*

In addition to standardized components (guides, sensors, frame profiles, etc.), the other printer components were obtained by 3D printing.
Having all the mechanical components of the printer designed, the motors for operating the arms of the printer were dimensioned.
The total mass of the components to be driven by the engines is calculated by formula (2):

$$M_{total} = 3 * M_{carriage} + M_{arms} + M_{head} + M_{extruder} \qquad (2)$$

$$M_{total} = 3 * 84g + 125g + 178g + 445g$$
$$M_{total} = 1000g$$

where,
M_{total} – total mass [g];
$M_{carriage}$ – carriage mass [g];
M_{arms} – arms mass [g];
M_{head} – printer head mass [g];
$M_{extruder}$ – extruder mass [g];

Calculation of the minimum power required for the engine to move the mass along the linear guide, in one second is the following:

$$F = m * g\ [N] \qquad (3)$$
$$\mathrm{F} = 0.350\mathrm{kg} * 9.81\frac{m}{s^2}$$
$$F = 3.4335\ N$$
$$P = \frac{F * S}{t}\ [\mathrm{W}] \qquad (4)$$

where,
P - power [W];
F - force [N];
S - linear distance [m];
t - time [s]

$$P = \frac{3.4335\ N * 0.5\ m}{1\ s}$$
$$P = 1.71675\ W$$

The stepper motor chosen for the linear motion is Nema17, model 42HN47-1684A, being a hybrid motor, having the following characteristics: step angle 0.9 °, nominal voltage 2.8v, nominal current 1.65 A, phase inductance 2.8 mH, etc.
Having all the components of the printer defined, the printer can be assembled, calibrated and tested.

Fig. 10. The prototype of the Delta printer

The theoretical specifications of the printer calculated based on the mechanical characteristics are:

- max rot/s: 0.76;
- max rot/min: 45.45;
- maximum power: 4.62 W;
- minimum step time: 3.30 ms;
- ideal voltage:53v;
- belt steps/mm:160;
- step resolution: 0.1 mm;
- micro step resolution: 0.00625 mm;

4. RESULTS

The printer's resolution can be calculated using one of the following equations:

$$printer\ resolution = \frac{1}{steps/mm} = \cdots mm \quad (5)$$

or

$$printer\ resolution = \frac{1000}{steps/mm} = \cdots \mu m \quad (6)$$

where,

$$\frac{\text{steps}}{\text{mm}} = \frac{\text{motor steps} * \text{ driver microsteps}}{\text{pitch of belt} * \text{pulley teeth}} \quad (7)$$

To start the calibration procedure, a manual pre-calibration of the printer was performed using the paper sheet method in the following points:

- Origin (0,0,0);
- Column X (-77.94, -45,0);
- Column Y (77.94, -45,0);
- Column Z (0, 90,0);

Using the open source utility "Delta Kinematics Calibration Tool" and an inductive sensor mounted in the print head, successive point measurement interactions were performed: origin, X column, x_opposite, Y column, y_opposite, Z column, z_opposite, final values of the interactions obtained with the "Delta Kinematics Calibration Tool" are written in the printer's EPROM and will continue to be used as the default parameters. After the printer was calibrated, it was tested. This test consisted of printing cubes with a side of 20 mm, and a wall thickness of 3 mm. This piece is shown in the figure below.

Fig. 11. Printed testing cubes

Three of the faces were marked with X, Y and Z, the average of the values obtained for 35 measurements is 19.71 mm for X, 20.05 mm for Y and 20.10 mm for Z. The figure below shows the histograms for each of the 3 faces.

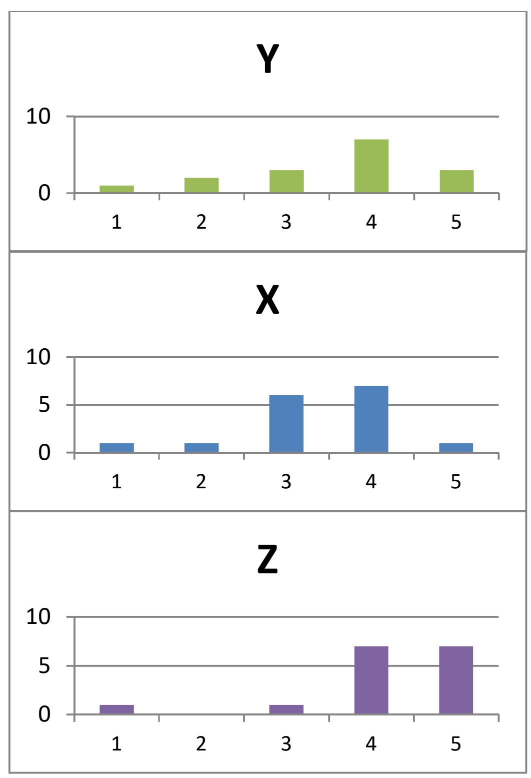

Fig. 12. Measurements of the testing cubes

After analyzing the measurements made with a micrometer, we can say that the dimensional accuracy is ± 0.2 mm.

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PROIECTAREA ŞI REALIZAREA STRUCTURII UNEI IMPRIMANTE 3D DELTA LINIAR

Rezumat: Lucrarea prezintă procesul de proiectare și dezvoltarea unei imprimante liniare Delta 3D. Structura mecanică cea mai frecvent utilizată pentru imprimantele 3D care utilizează depunere prin fuziune (FDM) se bazează pe mecanismul tradițional paralel. Această lucrare evidențiază avantajele unei imprimante 3D cu structură Delta în comparație cu structurile carteziene cu privire la diferite specificații tehnice, cum ar fi precizia, viteza de imprimare, grosimea stratului și dimensiunea totală a imprimantei. Instrumentele AHP au fost utilizate pentru a identifica designul optim al imprimantei și a fost concepută o matrice PUGH pentru a obține cel mai bun clasament al structurilor de imprimare 3D posibile. Precizia imprimantei dezvoltate a fost comparată cu alte imprimante carteziene disponibile pe piață pentru a evidenția precizia asociată cu viteza de imprimare a imprimantei Delta 3D.

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