RESEARCH INTO THE DESIGN AND CONSTRUCTION OF 3D PRINTERS FOR PLASTIC MATERIALS

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Abstract: In this work, the authors present solutions for improving the characteristics of 3D printers that use ABS or PLA plastic wire. Thus, the specific technological process can be carried out under optimum conditions. The study references machine-tool methodologies that are adapted for 3D printers. These solutions can reduce the footprint while improving the working speeds. Therefore, larger surfaces for the parts can be achieved without an excessive increase in the machine gauge. The presented constructive variants and kinematic designs can serve as a basis for developing new types of 3D printers for the industry and more.

Keywords: 3D printers, deposition rate, plastic parts, kinematic chains, pinion/rack mechanism

1. INTRODUCTION

3D printing represents an attractive alternative to traditional manufacturing processes [1]. Such technological advancements are employed for developing physical items based on virtual sketches or geometrical representations [2]. A wide range of industries rely on additive manufacturing. Examples include: agriculture, health care and interior design [3]. The machines employed in 3D printing operate along 3 axis of motion, and comprise at least a control system, electric drives, a wire feeder, a hot end and the print bed where the object is generated by means of material layer deposition [4]. In the present research, multiple kinematic chains that are employed in the design of 3D printers are discussed from printing speed and deposition rate perspectives. The performance limitations of the existing driving solutions are addressed by proposing gantry kinematic chain solutions that are inspired from machine tools.

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2. KINEMATIC STRUCTURE OF 3D PRINTERS

In general, 3D printers have the structure as shown in Figure 1 [5].

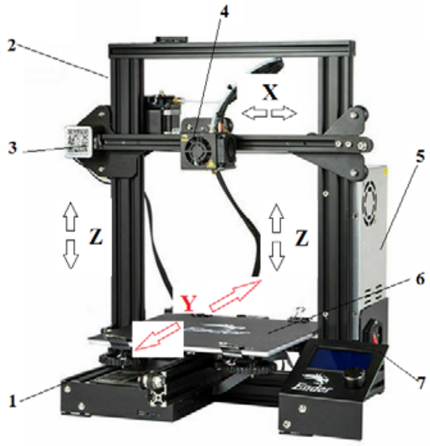

Fig.1. The structure of a 3D printer

The gantry 2 is attached to a fixed frame or bench. A beam 3 ensures the up and down movement of the work head 4 among the Z axis. On the other hand, the X axis displacement of the work head ensured among the beam 3. The last motion, on the Y axis is usually carried out by means of a table 6, in relation to bench 1. A power supply 5 and the control panel 7 feed the required input-output signals. The X and Y-axis movements are those that provide the contour of the deposition in a layer. The positioning of the next layer is done intermittently, on the Z-axis. The X and Y-axis movements are carried out continuously and simultaneously according to the program required for the execution of the part.

The continuous deposition process of the molten material shall be ensured, at the work head level, according to the system shown in Figure 2 [5].

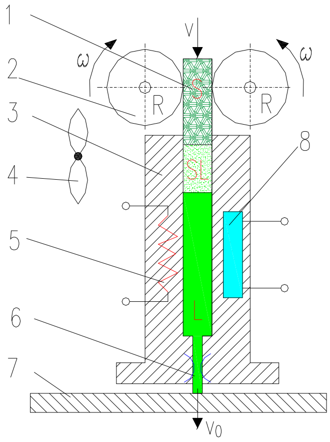

Fig.2. The wire driving system

The wire 1 is driven towards the rollers 2. They are identical and their aim is to drive the wire in the R radius area. The angular speed of the rollers is denoted ω. At this stage, the wire is considered in solid state (S). The head 3 includes a resistor 5 which warms up the wire, bringing it in a solid/liquid intermediate zone (SL). The material of the wire then becomes completely liquid (L) by heating it through the calibrated inlet 6 and reaches the deposition surface 7. The intermediate zone (SL) is cooled continuously by the heat sink and fan 4. Temperature control is achieved by using the thermocouple 8. If the wire is driven without slippage and the material is incomprehensible, than:

$$v = \omega \cdot R \tag{1}$$

$$v_0 = v \cdot \frac{D}{d} \tag{2}$$

Where: v represents the rate of descent of the wire, v_0 the rate of deposition of the molten material on the deposition surface, D the wire diameter and d the calibrated diameter (nozzle).

During the deposition, the material ejected at speed v_0, between the work head 3 and the deposition surface 7 there is a relative movement, on the X and Y axes, according to the diagrams depicted in Figure 3 with respect to Figure 1.

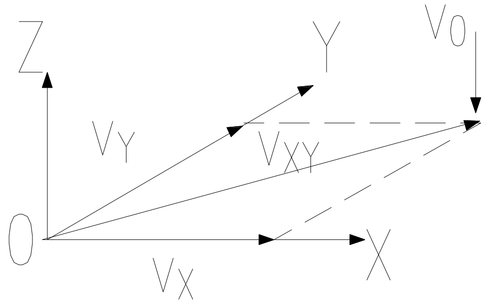

Fig.3. Operating speeds of 3D printers

The deposition rate v_0 depends on the factors specific to the technological process (material, wire diameter, calibrated diameter, working temperature, desired accuracy, etc.). The relative speed between the work head and the deposition surface has two components, one on each of the two X and Y axes.

Component X is usually provided by moving the head over the beam and component Y is the moving speed of the table on which the deposition is carried out. The v_{XY} speed achieved with two distinct kinematic chains is controlled for each component with the help of the specific program. This speed shall be related to the deposition rate, as shown in Figure 4.

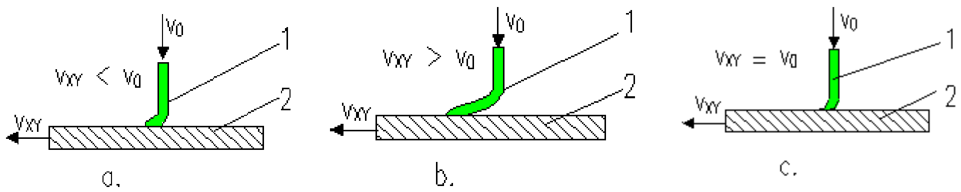

Fig.4. The deposition modality of the molten material

The wire 1 descends at the speed v_0 and deposits on surface 2 which travels at v_{XY} speed. If the speed v_{XY} is lower than the speed v_0 (fig.4.a) there is a risk that the material will deposit before it is evenly distributed. If v_{XY} is greater than the deposition rate, breaks or discontinuities may occur, as shown in Figure 4.b. The equality between the two speeds ensures the optimal printing process.

3. MATERIALS AND METHODS

Considering the speeds and forces developed during the operation of 3D printers and their relative low prices, it can be said that the designers of such machines can benefit from multiple driving solutions.

Kinematic driving chain with toothed belt

Figure 5 depicts one such solution, including a toothed bed.

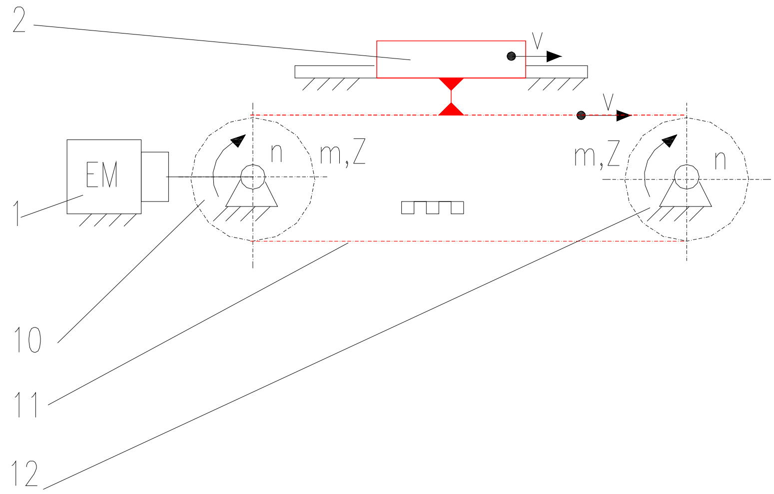

Fig.5. Kinematic driving chain with toothed belt

In the case of the toothed belt driving shown in Figure 5, the stepper motor 1 synchronously turns the two belt pulleys 10 and 12 resulting in the linear movement of belt 11 and table 2. The system is simple, frequently used due to its low price. Among its drawbacks, the back-moving clearance due to the elasticity of the belt, the belt fatigue over time and the machining and positioning errors that may occur can be remembered [6-8]. Also, the maximum loads that can act on the belt are limited, given its material properties.

The speed of the table can be written as:

$$v = n\frac{\pi m Z}{60} \tag{3}$$

Kinematic chains with pinion/rack mechanisms

Pinion/rack mechanisms can be developed in two configurations (Figure 6 a and b).

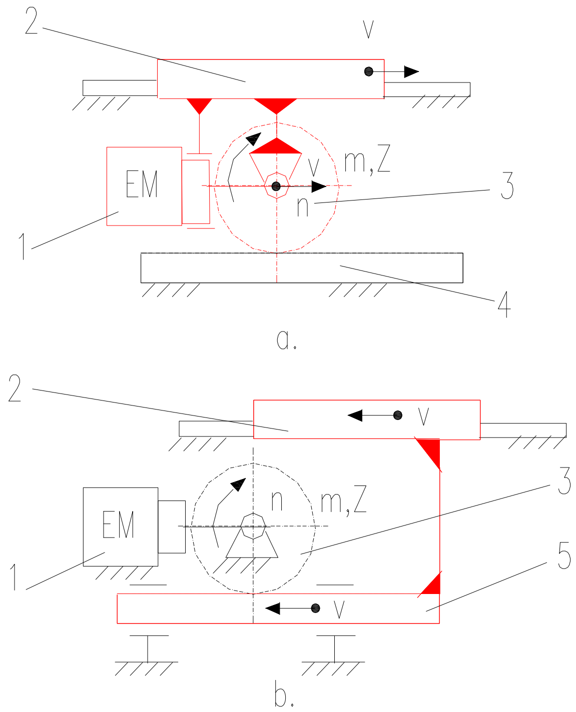

Fig. 6. Kinematic chains with pinion/rack mechanisms

In the case shown in Figure 6a, the motor (1) rotates the pinion (3) at speed n (with Z teeth and with module m) that rolls on the fixed rack 4. The table 2 is also driven in the translation motion. The system is typically used for long strokes and also for large machine tools, with strokes that exceed 5 – 6 m [7-9].

The solution shown in Figure 6b performs the translation movement of table 2 at the same time as the movement of the moving rack 5. In this case, motor 1 turns pinion 2 which no longer has a translational motion. These systems allow high speeds under high accuracy conditions for both positioning and for the technology cycle, if equipped with back-moving clearance absorbing systems [8,10]. In both cases, the speed is also determined by relation (3).

Kinematic driving chain with bolt and nut mechanisms

The precision bolts used in the kinematic chains are usually equipped with back-moving clearance absorbing systems [8,10,11]. In this regard, trapezoidal-shaped screws or ball screws [6,7,11] are two of the most popular choices. The two kinematic variants are emphasized in Figure 7, depending on the desired stroke.

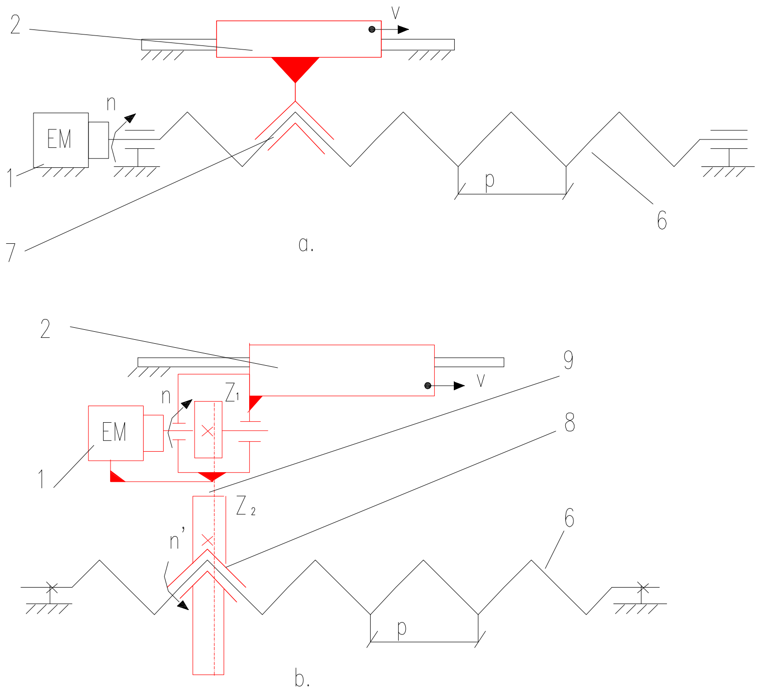

Fig.7. Kinematic driving chain with bolt and nut mechanisms

As shown in Figure 7, the electric motor 1 drives directly or through a reduction gear (not shown in the figure) bolt 7 which, using nut 6, translates the table 2.

If bolt 1 is fixed, as shown in Figure 7b, motor 1 is joined to table 2 and by means of the Z1/Z2 transmission, motor 1 operates rotating nut 8, resulting in the translation of the table-motor assembly. The Z1/Z2 transmission can be a tooth gear drive or a toothed belt.

Irrespective of the chosen option, the v speed will be:

$$v = n \cdot \frac{P}{60} \tag{4}$$

Of all systems shown above, the ball screws are the most accurate and can withstand the most sever loading conditions.

If the same input speed is considered in the rack-pinion or toothed belt systems, it develops higher speeds than those with the nut bolt. The minimum number of teeth of a gear or of a toothed belt gear is usually greater than 20. The πm product shall be greater than 60. Comparing relationships (3) and (4), it is noted that a pinion-rack system with module m=1 achieves a speed which, in order to be achieved with the bolt-nut mechanism, would require a p > 30mm pitch. This cannot be achieved.

4. RESULTS AND DISCUSSIONS

In the construction of the machine tools, there are two types of frame structures (gantry) that can also be taken into account in the design of 3D printers. They are shown in Figure 8.

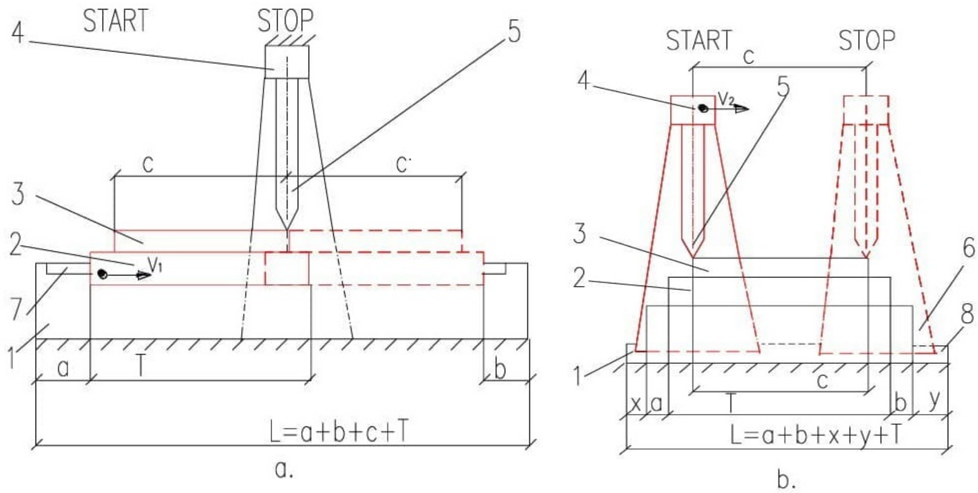

Fig.8. Structures for Gantry machines

The following notations are used in Figure 8: 1- bench, 2- table carriage, 3- board for depositions, 4- gantry, 5- work head, 6- carriages under the posts, 7- table guides, 8- carriage guides under the posts, a, b- dimension of the bench, c- working stroke, x, y- the cross dimensions of the carriages under the posts, T –length of the table (on the Y direction), L- the machine gauge dimension (on the Y direction).

The first variant is shown in Figure 8a and is characterized by the fact that the gantry is fixed and the table moves in the Y direction. The motion takes place at v1 speed on the entire c stroke. In this case, the L machine gauge dimension on the Y direction is:

$$L = a + b + c + T \tag{5}$$

If the table is fixed and the gantry moves at speed v2, on guides 8 with the carriages 6, as shown in Figure 8b, the machine gauge is:

$$L = a + b + x + y + T \tag{6}$$

By comparing relationships (5) and (6), regardless of the the mobile gantry version used, the machine gauge is smaller, with respect to the relationship:

$$c > x + y \tag{7}$$

An interesting solution, resulting from the two variants in Figure 8, is illustrated in Figure 9 [10].

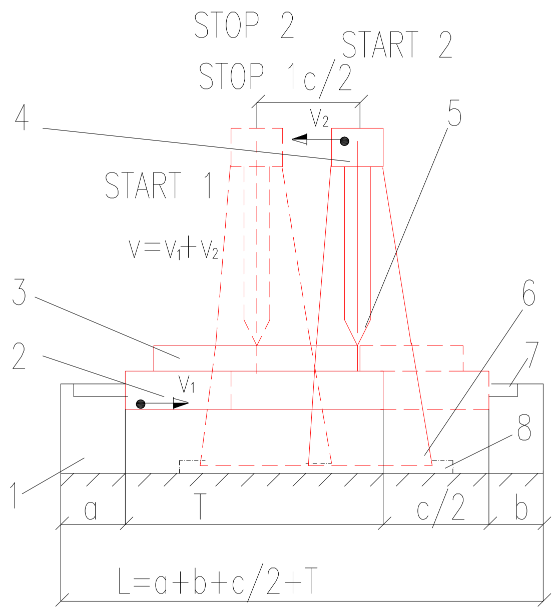

Fig.9. The Gantry structure with double movement

In this case, the stroke c is achieved by moving the table on the c/2 stroke and the gantry on the c/2 stroke.

With this solution, the speed between the deposition head and the deposition surface can be at maximum speed ν= ν1+ ν2. In this case, the gauge on the Y axis becomes:

$$L = a + b + \frac{c}{2} + T \tag{8}$$

Theoretically, this gauge falls between the two constructive solutions depicted above.

The kinematic design of the machine in this case can be achieved by means of three servo motors, as shown in Figure 10.

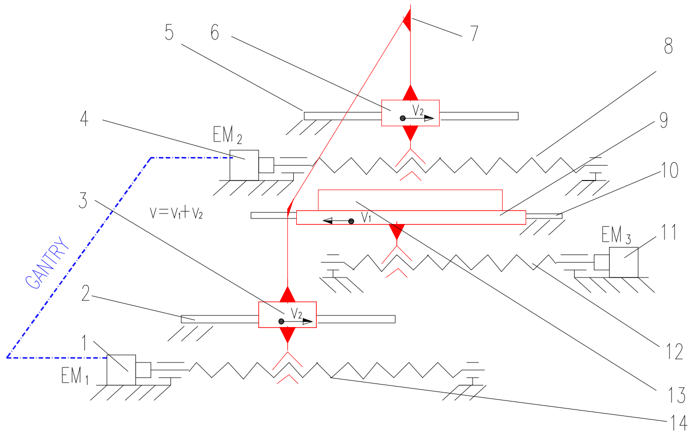

Fig.10. The kinematic diagram for the low-gauge Gantry machine

Servo motors 1 (EM1) and 4 (EM2) work simultaneously (Gantry) and provide movement of carriages 3 and 6 and of gantry 7 with the help of precision screws 8 and 14, on the guides 2 and 5 at v2 speed. Servo motor 11 (EM3) moves table 9, on guides 10, at speed v1. The material deposition is carried out on plate 13. The drives can be controlled independently, with programmable speeds, but also simultaneously. In this case, the speed will be the sum of the two speeds v1 and v2.

Also for moving the table and gantry, but not independently, the solution shown in the kinematic diagram in Figure 11 can be employed.

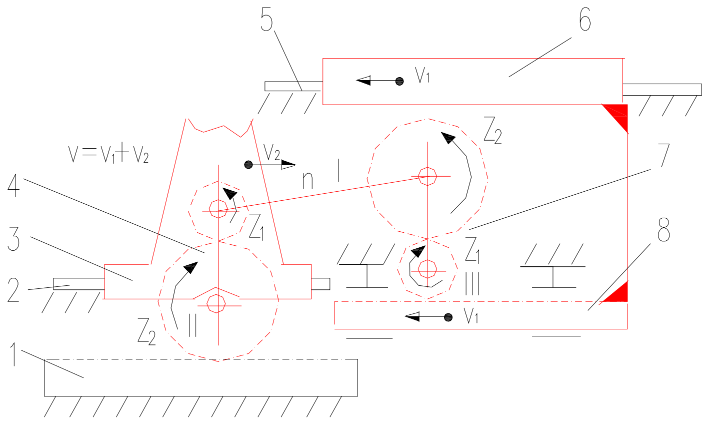

Fig.11. The kinematic diagram to sum movement speeds

There are two types of drives (depending on the Gantry), usually in the gantry post area. The carriages under posts 3 move onto guides 2 on the fixed racks 1. The motion is transferred to the level of shaft I from two servo motors not shown in the figure. By means of gears Z1 and Z2, pinions Z2 move around axis II, the gantry's 4 translation occurring at speed v2. Also from axis I, the movement reaches the shaft III and, by means of gears drives 7 (Z2/Z1) racks 8 move table 6 at speed v1 on guides 5. These systems are also equipped with a back-moving clearance absorbing system [8, 10, 11].

6. Conclusions

The design and construction of 3D printers must be in such a way that the parts made of plastic meet the required precision requirements. The deposition speed, achieved using melting and feed systems, must be observed and kept constant. For this, it is recommended to use feed systems with no clearance or slips and permanent control of the working temperature. The correlation of the deposition rate shall be done by continuously controlling the feed speeds in the X and Y axes, with particular attention being paid to interpolation. Due to economic reasons and not only, low-gauge machines are preferred, easy to position and use. Feed systems shall be designed in such a way that the back-moving clearances should be as small as possible. By using correctly chosen kinematic solutions, compact and high precision machines can be made.

REFERENCES

[1]. **Chadha, U, Abrol,A., Vora, N.P., Tiwari, A., Shanker, S.K., Selvaraj, S. K.,** Performance evaluation of 3D printing technologies: a review, recent advances, current challenges, and future directions. Progress in Additive Manufacturing, 2022, pp.1-34.

[2]. **Livesu, M., Ellero, S. Martínez, J., Lefebvre, S., Attene, M.**, *From 3D models to 3D prints: an overview of the processing pipeline*, Computer Graphics Forum, 36(2), 2017, pp. 537-564.

[3]. **Shahrubudin, N., Lee, T.C., Ramlan, R.** *An overview on 3D printing technology: Technological, materials, and applications*, Procedia Manufacturing, 35, 2019, pp. 1286-1296.

[4]. **Pisarciuc, C.** *Analysis and evaluation of the main parameters for the 3D printing process*, Nonconventional Technologies Review/Revista de Tehnologii Neconventionale, 23(2), 2019, pp. 21-28.

[5]. **Motomancea, A., Bucuresteanu, A., Prodan, D.,** *Execution of Non-Metallic or Metallic Duplicates, Cast with 3D Scanners and 3D printers*, Rev. de Materiale Plastice, 56(1), 2019, pp. 6-10.

[6]. **Joshi, P.H.,** *Machine Tools Handbook Design and Operation*, Tata McGraw-Hill Publishing Company Limited, New Delhi, India, 2007.

[7]. **Perovic, B.,** *Handbuch Werkzeug-maschinen,* Carl Hanser Verlag Munchen Wien, 2006.

[8]. **Prodan, D.,** *Heavy Duty Machine Tools Mechanical and Hydraulic Systems*, Printech Publishing House, Bucharest, 2010, pp. 227.

[9]. **Bucuresteanu, A., Prodan, D., Motomancea, A.,** *Execution of Plastic Parts Using 3D Scanner and 3D Printers*, Rev de Materiale Plastice, 55(2), 2018, pp. 215-218.

[10]. **Besharati, S.R.,** *Design and Manufacturing of New CNC Gantry Machine with Double Motion Feed Drive System*, PhD Thesis, Faculty of Engineering, University of Malaya Kuala Lumpur, 2015.

[11]. **Teixido, C., Jouanne, J.C., Bauwe, B., Chambraud, P., Ignatio, G., Guerin, C.** *Guide de construction mecanique*, Delagrave Edition Paris, 2000.