Designing of 3D Printer Based on Polar Coordinate System

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Abstract – *The application of 3D printing technology in manufacturing is becoming more and more popular, that to production has increasing potential in many fields. This paper describes the process of designing of 3D printers, using polar coordinates to control axis movement. To solve problems related to control the movement of printing axes during the 3D printing process. The research used the Computer Aid Design (CAD) method through Inventor software to create a new model 3D printer, with operating mechanisms and improvements to meet the needs of complex 3D product design and production. The drive shafts are controlled by the main circuit through the Gcode language adapted from the CAD model. Using the polar coordinate system allows converting printing axis movements from Cartesian coordinates (x, y, z) to polar coordinates (r, θ, φ) to reduce parts in the machine structure, thereby creating a compact 3D printer at a low cost. This design is intended to contribute to diversifying printer models and applications to create low-cost 3D printers.*

Key Words: *3D printer, Computer Aid Design, polar coordinate*

1. INTRODUCTION

3D printing, also known as additive manufacturing, has developed rapidly and has demonstrated great potential for manufacturing in many industrial areas [1, 2]. 3D printing technology that is changing the way we perceive the realization of ideas as well as design and production is 3D Printing technology, known for many names like Fabrication Additive, Layered Manufacturing or additive manufacturing [3]. In recent decades, 3D printing technology has developed rapidly as a technology with many promises, bringing optimal design capabilities to help save materials, time, and simplify the machining process. created, with many construction sizes, operating mechanisms as well as constantly updated with new features, thanks to which 3D printers have gradually changed the way we think about creating new products with many different types of materials [4, 5].

Currently, although many important achievements have been achieved, 3D printing technology is still being researched, and developing more features to exploit the machine's advantages in many fields. At the same time, the production of complex products is no longer limited and can be easily customized according to specific needs, such as modern houses that have been printed by 3D printers in recent times. in the shortest time with the most economical cost, or bone or tooth parts are scanned and printed with special materials to replace damaged parts inside the human body, or complex mechanical parts that can only be produced with the 3D printer for metal materials [6]. General characteristics 3D printers operate based on basic mathematical equations of motion such as Cartesian, Delta, and especially Polar Coordinates [7]. Polar coordinates provide the ability to perform bending and twisting movements with ease, whereas Cartesian coordinates have difficulty performing these movements effectively when combined at the same time. three to four axial movements to create a curved profile. With the advantage of free movement in three-dimensional space, especially when printing complex products, polar coordinate system 3D printers have the ability to optimize paths and move from one point to another simply. By combining only two arm axes and a rotary table, it is easy to create complex profiles, especially products with cylindrical and symmetrical profiles, helping to cut the time and energy needed to complete into product. In order to contribute a solution for 3D printer manufacturing that provides flexibility for drive shafts, the development of a 3D Printer that uses a Polar Coordinate System to improve printing performance is very suitable for the industrial context and current technology.

This paper describes the process of designing of 3D printers, using polar coordinates to control axis movement. To solve problems related to control the movement of printing axes during the 3D printing process. The drive shafts are controlled by the main circuit through the Gcode language adapted from the CAD model. Using polar coordinates (r, θ, φ) that to reduce components in the 3D printing machine. The article also describes the calculation of stress, determining the areas subject to concentrated stress and displacement of the manipulator then choose a suitable shape of the manipulator arm. This design is intended to contribute to diversifying printer models and applications to create low-cost 3D printers.

2. MACHINE DESIGN

2.1 Machine cofiguration

The 3D printer in this design utilizes angular coordinates (θ) and distance (r) from the center of the object to be printed. The machine has three principal movements.

Theta Axis (θ) Movement: The Theta axis corresponds to the rotational movement of the print bed. To alter the Theta angle, the 3D printer controls a stepper motor to rotate the print bed, facilitating this axis's movement. This allows the 3D printer to position the print head around the main axis at various angles.

Radius Axis (r) Movement: The Radius axis corresponds to the distance φ pattern from the center of the object to be printed to the print head. To change this distance, the 3D printer utilizes an arm mechanism carrying the hotend. This allows the 3D printer to adjust the distance, also known as the proximity or remoteness, of the print head from the coordinates to be printed according to the initial programming.

Z-Axis Movement: In addition to the Theta and Radius axes, the 3D printer continues to use the Z-axis to adjust the height of the print head relative to the print bed. This allows the 3D printer to create new print layers on the surface of the objects as they are being printed, thereby forming the objects' height according to the layer height from the slicer setting.

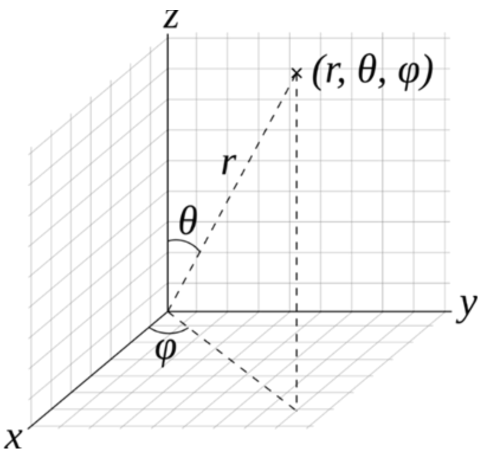


***Figure** 1. The image depicts the location of a coordinate in space according to the polar coordinate system.*

As the polar coordinate-based 3D printer operates, it transmits signal values for the theta angles, radius distances, and Z heights to create the desired 3D print model. These data are converted from Cartesian coordinates with X, Y values to polar coordinates into r and φ, with $r \geq 0$ and φ in the range of $(-\pi, \pi)$, following the Eq (1)

$$r = \sqrt{\left(x^2 + y^2\right)}$$
$$\varphi = a\tan\left(y / x\right) \qquad (1)$$

The device's operational approach will be discussed in depth in this section. The research team works on the computation and design of the 3D printer using the required electronic devices and components and polar coordinate equations. Thanks to the new design based on the hinge design, a couple of components, including the swing arm assembly holding the hotend, will fit well with the Z-axis motion assembly. As a result, as shown in Figure 2, the rotating table spins in accordance with the polar angle while working with the X-axis arm assembly to direct the extrusion assembly as it goes from the center to the outer diameter and back again. This is done by following the coordinates of the printed layer. The device's manner of operation causes the molten material to be molded on the rotating table before being extruded via the nozzle.

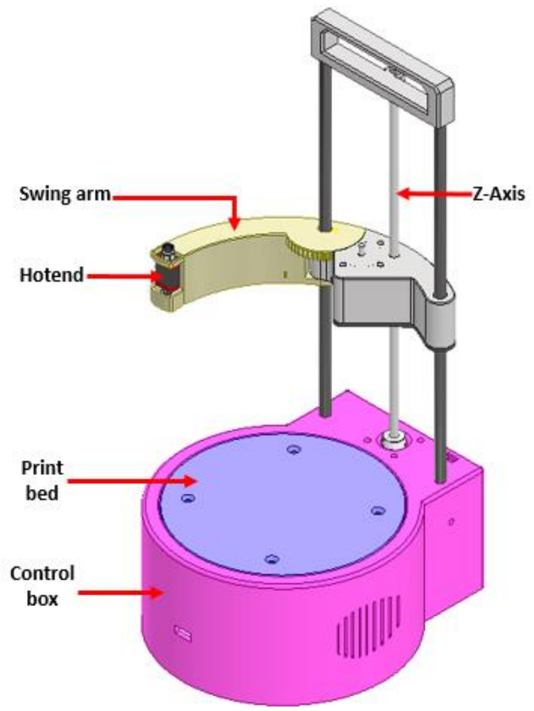


***Figure 2.** The structure of a 3D printer is based on the polar coordinate system.*

Based on the polar coordinate system algorithm, the research team applies this system to the stages and joints of the motion axes, converting coordinates from Cartesian coordinates to polar coordinates [8]. Accordingly, the motion axes are oriented based on angles and radians, rather than determining direction by length, width, and height. This allows the 3D printer to optimize the build size but with an overall smaller design and simpler structure compared to machines with the same print volume, ensuring that the printed details are accurately produced, especially for cylindrical objects or those with radial symmetry.

2.2 Component design

Figure 3 shows the decomposition design of the structures and components that have been calculated, designed, and simulated in detail based on the assembly environment and decomposition presentation provided by the software. According to the machine design, there are proposed parameters such as overall dimensions of 210x210x350mm, a weight of about 5 kg, with the Y turntable axis acting as a circular motion printing table, the Z-axis moving vertically thanks to the transmission of the drive shaft and is designed to carry the X-axis arm assembly and print head and the extrusion of printing material contained inside the machine body. All motions of the shafts are driven via stepper motors.

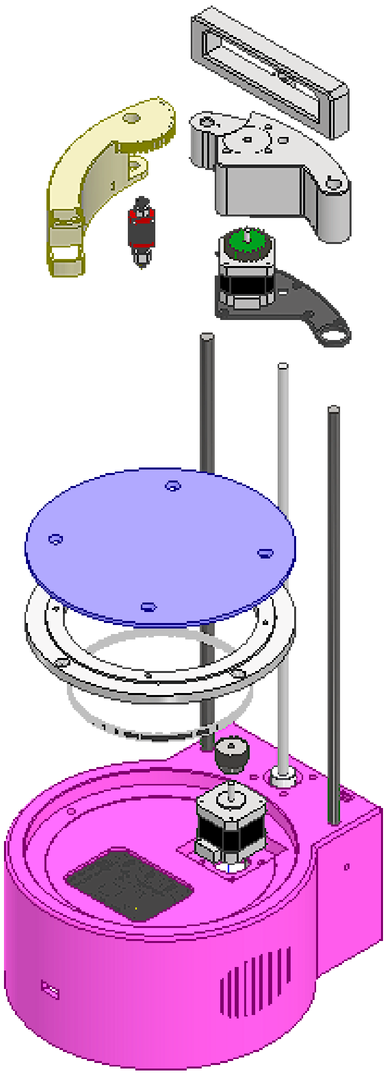


Figure 3. *Parts of the machine decomposition design*

Turntable design

The Y-axis turntable with the table gear coupling mechanism is composed of a rotating disc with a toothed pitch, and a silver ring with a roller ball acting as a bearing to ensure stability and long-term operation as well as to withstand changes in direction continuously of the turntable, the detailed assembly is arranged above the machine body according to Figure 3. The turntable Y-axis rotates by the transmission of a stepper motor linked to a GT2-T40 pulley along with a toothed turntable. The transmission ratio (I) can be calculated as Eq (2).

$$I = \frac{Z_2}{Z_1} \tag{2}$$

The large wheel of the turntable with Z_2=214 teeth and the small wheel pulley with Z_1=40 teeth, substitute the number of teeth into the Eq (2). Then rotate one revolution of the printing table, the motor must rotate 5.35 revolutions to achieve the necessary gear ratio.

Machine arm design

Based on the polar coordinate system the position of the system's coordinates in three-dimensional space is shown in Figure 1. The X-axis is designed with a moving arm-like mechanism. Based on the angle α, the table rotates on the Y-axis, gradually translating to the printed layer height of the Z-axis and the material extruder. To reduce the load on the Z-axis using the above motion method, the weight of the X-axis must be reduced to the maximum through design. At the same time, to limit the inertial force caused by the X- axis drive motor, the authors consider using an indirect extruder along with a drive motor of small size and weight, such as the mass of the drive motors. The design approach shown in Figure 3, includes the X-drive carried on the Z-axis, and the arm and the extrusion are arranged above the turntable.

Machine frame design

The frame of the machine is designed with the purpose of protecting the internal components while taking advantage of the space to create positioning and mounting positions that can be fixed with hexagonal screws according to the design to assemble the parts, control circuit boards, and electrical devices, along with executive components. That contributes to increasing the weight of the machine frame. Therefore, it limits the influence of inertial forces created by the machine's rotation shafts during operation and helps the machine's stability and durability during use. Except for electrical components and mechanical parts that 3D printing technology cannot produce yet. For designs with high complexity including parts and remaining machine structures, the authors consider using 3D printing technology to create a small size, easy to produce and manufacture. In order to complete the process from CAD model to fabrication for a 3D printer, the functional clusters also need appropriate mechanical and electronic parts has been selected and listed in Table 1.

Table 1. *Parameter of chosen components*

Components	Parameters
Step motors (Y, Z, E0)	Nema17/0.9°; 42×42×38 mm
Step motors (X)	Nema17/0.9°; 42×42×34 mm
Circular motion Y-axis	Timing belts GT2; Pully 40 tooth
Linear motion Z-axis	Lead screw T8; pitch 2 mm/rev

3. RESULTS AND DISCUSSION.

3.1 Assembly simulation .

After creating a 3D model and assembling the machine according to the polar coordinate system and the machine's operating functions. Based on the simulation assembly environment of Inventor, set up the polar coordinate system 3D printer as follows:

- Configure the polar coordinate system for the 3D printer using the coordinate system option in the Inventor program.
- Set angle and origin parameters of motion axis for 3D model of axes, and parts in 3D printer model.

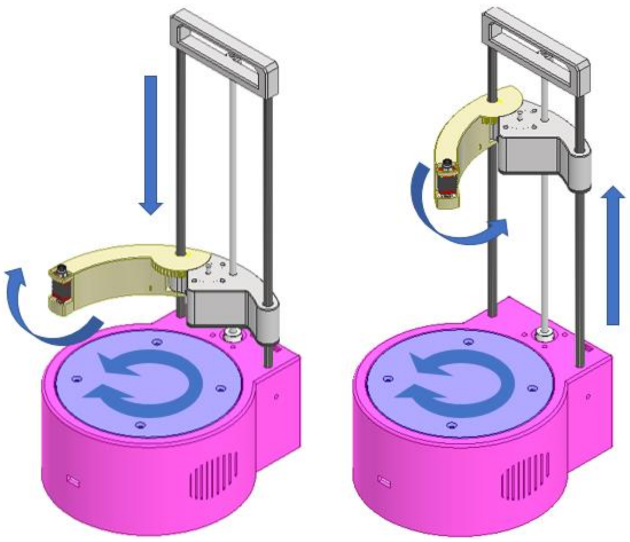


Figure 4. *Motion of parts in a polar coordinate system.*

Axial motion simulation based on polar coordinates is shown in Figure 4 in two states from left to right.

- State 1: The arm assembly is controlled downward by the Z-axis linear transmission system, and at the same time the swing arm carrying the material extrusion moves at an angle α from the center of the Y-axis turntable outward, combined with a distance. This method allows rotation in both directions of the printing table, creating a combination of the motion of the axes on the 3D printer.
- State 2: The swing arm assembly is controlled upward by the Z-axis transmission system, and at the same time the arm part carrying the material extrusion moves at an angle α from outside the printing table to the center of the Y-axis turntable, combined with the distance created from the allowed rotation in both directions of the printing bed, creating a combination of movements of the axes on the 3D printer.

Considering the simulation process, the swing arm assembly is the part that receives the sum of the stresses generated from the lifting and lowering transmission of the Z-axis, the arm part's transmission at angle α, the mass of the material extrusion, and the force that is created from the material extrusion. Therefore, it can evaluate the effectiveness of the moving axes based on the polar coordinate system, identify defects that need to be optimized, and adjust the design to achieve optimal results for 3D printer applications polar coordinate system.

3.2 Stress simulation.

Considering that the perpendicular position between the swing arm and the meshing teeth is the area with the weakest structure in the machine design, to meet the force-bearing capacity and increase the durability of the important position is swing arm shaft. The research team set up the parameters as shown in Figure 5. Simulation of the stress analysis environment, proceeding in the following order, adding details on how to analyze force in the stress analysis environment, and choosing the settings. Establish the impact force, determine the fixed position, select the direction plane and position of force application, set the final impact force value, simulation process and analyze the results which to find the impact force come up with a suitable design plan.

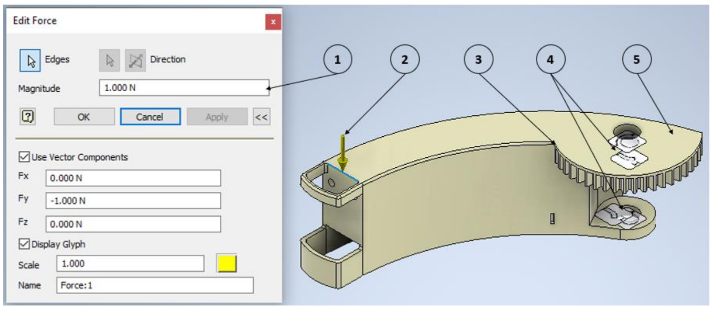


Figure 5. *Stress simulation setup for the swing arm- 1. Applied force, 2. Position of applied force representing the stress of the print head assembly and pressure during material extrusion, 3. Investigation points, 4. Fixed positions, 5. Printing swing armprinted of ABS material.*

Simulation setup parameters and simulation results are presented in Tables 2 and 3.

Table 2. *Simulation results.*

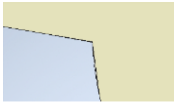
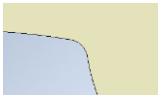
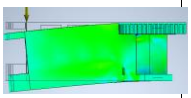
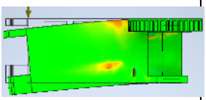
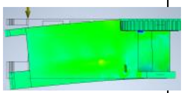
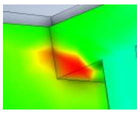
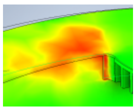
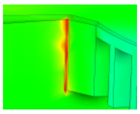
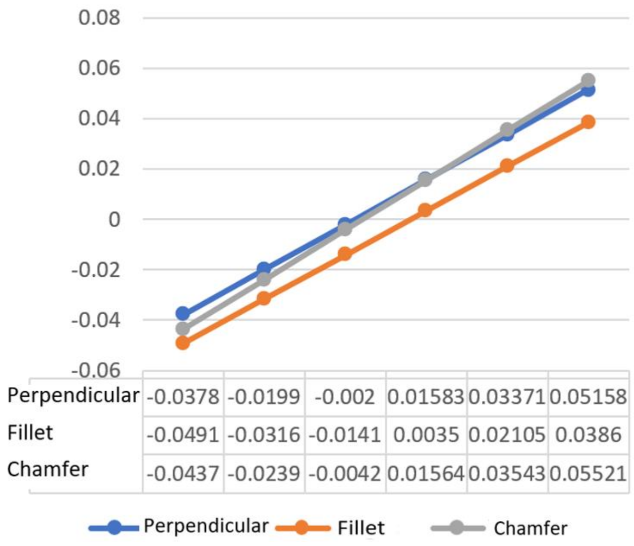
	Perpendicular	Rounded Corner	Chamfer Corner
Adjacent angle			
Displacement			
Stress zone			

Table 3. *Parameter setting in simulation.*

Parameter	Unit	Value	Stress
Perpendicular	degree	90	.0515
Fillet	mm	4	.0386
Chamfer	mm	4	.0552

Table 4. *Results obtained from the simulated force experiment, units in Mpa*



The distribution of stress has been simulated on Inventor software for three different design directions at the junction between the teeth and the arm carrying the print head. Simulation results have obtained data as shown in Table 4 and the analysis results are as follows

- Perpendicular case: the force is concentrated mainly at the location below the junction. Specifically, the largest impact force reaches a value of 0.0515. Points out that square design can lead to potential weakness if the force is too concentrated in a small area.

- Fillet case: even though the force is concentrated at the junction, the maximum impact force value is up to 0.0552, the highest in the three experiments. This shows that the corner flap design option is not the optimal choice when wanting to minimize stress at the junction.

- Chamfer case: impact force is evenly distributed throughout the contact area, minimizing the concentration of force. As a result, the maximum impact force reaches 0.0386, lower than the perpendicular option. This indicates that cornering can help optimize force distribution, minimizing the risk of damage or fatigue at the interface, and increasing confidence in the printer's accuracy.

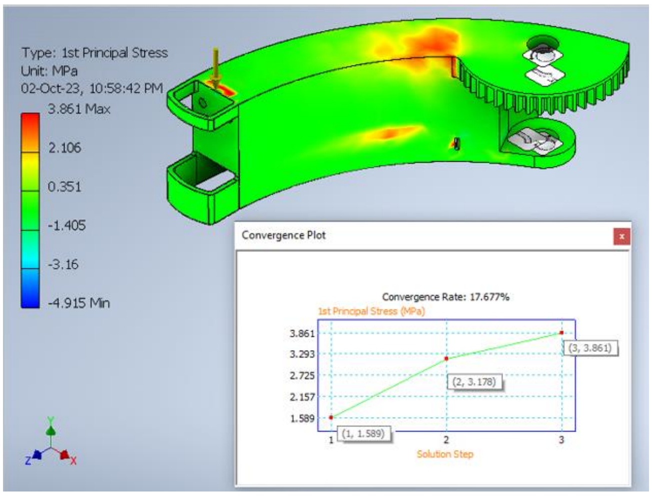


Figure 6. *Simulation of stress distribution on the swing arm*

Based on the above data and analysis, the rounded corner design shows that it has the best ability to disperse force, reduces maximum pressure concentrated in one location, and can help increase longevity and durability. durability for the moving system, the influence amplitude of the stress is shown in Figure 6. The stress ranges from (1,589~ 3,178) Mpa, and the stress causing deformation is up to 3,861Mpa. On the other hand, the total mass of the print head and the maximum stress created by the material extrusion is only 1N/(mm)^2 ⟺ 1 Mpa. It can be concluded that the corner design option helps the arm withstand stress three times greater than actual working needs, which is an especially important factor in 3D printer movements, where the risk of failure is minimized and tolerances are controlled. of the printed matter is the main factor.

4. CONCLUSIONS

This study has presented the research process aimed at creating a 3D printer that provides a compact size and low cost while still being able to handle the demands of manufacturing and fabricating complex products. The research has integrated the polar coordinate system into the design of the motion mechanism for the 3D printer. As a result, the machine's structure requires considerably fewer components, and the printing axis movements are successfully transformed from the Cartesian coordinate system to the polar coordinate system. Calculation of stress, determining the areas subject to concentrated stress, and displacement of the manipulator have been done and discussed. Then a suitable shape for the swing arm has been presented. This design not only diversifies printer models and expands their applications but also opens up new creative opportunities and achieves substantial cost savings in the manufacturing sector.

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