

3D printed gyroscopes: Design, fabrication, and future prospects of spinning mass systems

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Abstract. Gyroscopes are valuable devices that are used in the calculation of angular and orientation speed in any kind of mechanical machine. In this paper, spinning mass mechanical gyroscopes will be discussed and how they can be additively printed. The article highlights the new technology, 3D printing, in the manufacturing of a gyroscope with increased customization, weight reduction and low-cost features. Various types of gyroscopes are provided, including mechanical, optical, MEMS and quantum gyroscopes to provide a larger picture of technology. The design, selection of the material (PLA PRO+ in particular) and fabrication and calibration are also presented in the paper. The findings suggest additive manufacturing can be rather beneficial in the context of the production of complex geometries and lightweight structures without disrupting the functionality. In the future, hopefully, it will be integrated with more advanced sensor and control systems that will allow it to be precise and expand its field of use.

Introduction

Gyroscopes are basic tools employed to measure the orientation and angular velocity of mechanical and electromechanical systems. A standard gyroscope is made up of a rapidly rotating rotor mounted on gimbals, so that the gyroscope can retain its orientation with respect to external movement. This is controlled by the conservation of angular momentum which says that a rotating body resists any change in its axis unless acted on by an external torque [1-4]. Angular dynamics controls the working principle of a spinning mass gyroscope. Angular momentum is a measure of the magnitude and direction of rotation that is conserved when no external disturbances are present. The correlation between the angular velocity and the angular momentum is given as:

$$L = I\omega$$

In which L is angular momentum, I is the moment of inertia and ω is the angular velocity. These vectors are directed by the right-hand rule and as such, the angular momentum and the angular velocity are parallel to the axis of rotation and normal to the plane of motion respectively [5-8]. Torque is essential in altering this momentum resulting in phenomena like precession that is generally widely experienced in the gyroscopic systems [9].

Gyroscopic Torque and Precession

$$\tau = \frac{dL}{dt} = I\omega\Omega$$



Where, τ =applied torque, L =angular momentum, I =moment of inertia, ω =spin angular velocity, Ω =precessional angular velocity

This equation characterizes the effect of gyroscopes whereby a torque applied causes precession, which is not direct rotation. This is the fundamental concept of the stability of spinning mass gyroscopes [9-12]. In the past gyroscopes are an extension of the primitive spinning top to advanced systems used in aerospace, robotics and consumer electronics. Even though modern technologies have optical, MEMS, and quantum gyroscopes, spinning-mass mechanical gyroscopes are still extensively used because of their simplicity, durability and dependence on complex electronics. Over the recent years, mechanical design has been completely reshaped by additive manufacturing (3D printing). In contrast to older subtractive techniques, it is made of components built in layers of digital models, allowing complex geometries, minimized material waste, and high precision [6]. It is especially advantageous to the gyroscopes in which the mass distribution is optimised and structures are lightweight, which improves their work. A rapid prototyping and design optimization is also enabled by additive manufacturing. Lightweight materials can be used to fabricate components such as housings, brackets and supports without any loss in strength and can be refined more quickly than normal construction methods [7], [8].

Figure 1 depicts a conceptual spinning-mass gyroscope with rotor, gimbal and frame, which illustrates its stability on its axis of rotation. Figure 2 shows the additive manufacturing workflow of CAD modelling to final assembly.

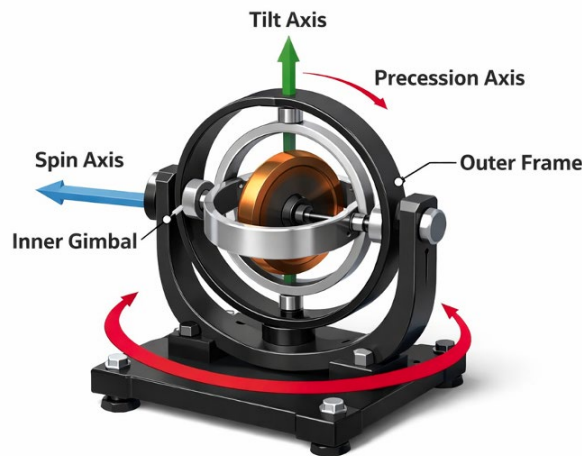


Figure 1: Conceptual diagram of a mechanical gyroscope of spinning mass with rotor, gimbal, and frame.

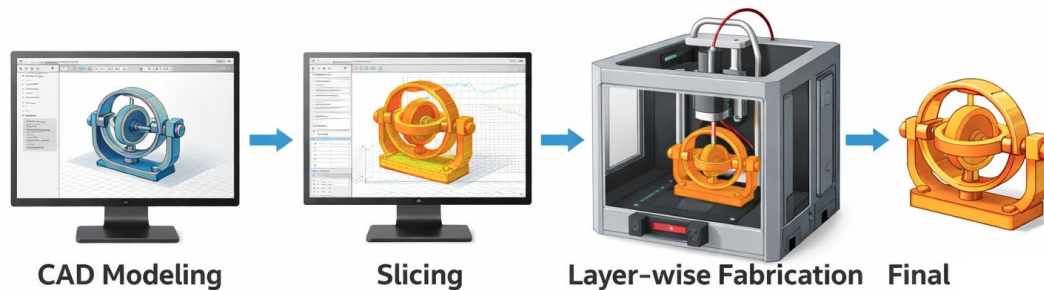


Figure 2: Additive manufacturing process workflow, starting with the CAD model and then the final component productions.

Additive Manufacturing and Classification of Gyroscopes

Figure 3 shows the hierarchy of classification of gyroscopes, where the shift to more sophisticated optical and quantum technologies can be seen. The figure also highlights the tradeoff among accuracy, cost, and complexity among the types [13-18].

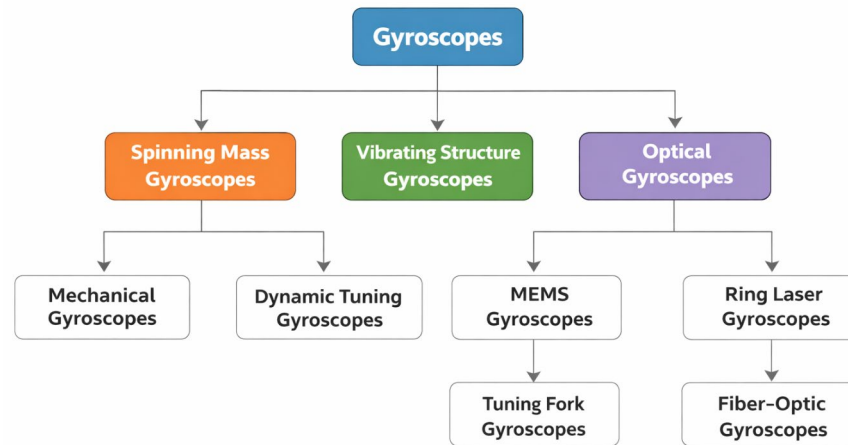


Figure 3: Classification of gyroscopes based on operating principles and sensing mechanisms.

Role of Additive Manufacturing in Gyroscope Development

The use of additive manufacturing (AM), also known as 3D printing, has brought a paradigm shift in producing mechanical systems. Unlike the traditional subtractive processes in which the material is shaped by removing it to create the necessary shape, AM is deposited in layers depending on digital models. The design methodology enables unprecedented design freedom and good utilization of materials [6], [19-20]. Gyroscopes are particularly useful in terms of the additive manufacturing in view of the geometrical and functional complexity of gyroscopic assemblies. Others include gimbal rings, brackets, housings, support structures and in most instances they are complex shapes that are difficult or costly to produce using traditional machining methods. These elements can be produced as built-in elements in the AM, which simplify the assembly procedure and boost the structural integrity [21].

One of the greatest benefits of AM is that one can make lightweight parts without compromising the mechanical strength. This is achieved through optimisation of internal structures such as lattice geometries which lower mass but do not lose stiffness. The weight loss is directly proportional to the dynamic performance and the power consumption is also less in systems with gyroscopes, especially in unmanned aerial vehicles (UAVs) and handheld devices. Another one is the additive manufacturing which enables rapid prototyping and design. The digital models enable the engineers to rapidly transform and develop new parts which can be refined in terms of mass distribution, center of gravity and rotational stability far quicker. It is a very important feature as far as the design of the gyroscopes is concerned because even the slightest difference can be fatal to the performance characteristics.

The additive manufacturing process used in the study is depicted in figure 4 and comprises of CAD model, slicing, layer-by-layer fabrication and post-processing. The figure illustrates how the digital design is directly transformed into physical components to produce a high degree of accuracy and repeatability.

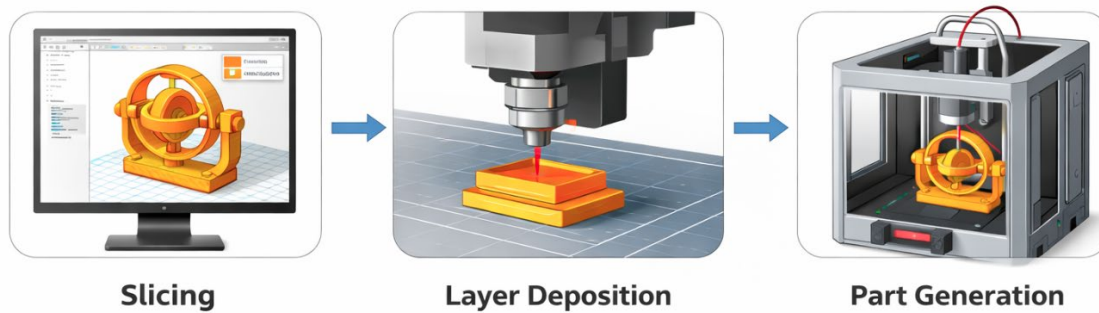


Figure 4: Additive manufacturing pipeline illustrating slicing, layer deposition, and part generation.

Integration of Conventional Components

Even though additive manufacturing is flexible, not all the components are converted to additive manufacturing due to performance. These include bearings, fasteners, motors and power transmission such as pulleys and belts. Particular attention should be paid to bearings, which reduce friction, and enable a rotational movement to be carried out without any complications, therefore, the quality of gyroscopic retention of stability [13]. The table 1 lists the traditional components that make up the system and they consisted of aluminum bars, bolts and nuts, bearings, batteries, servo controllers and multi-rotor assemblies. The choice of such materials can be explained by their mechanical stability and their ability to be compatible with the 3D printed structure. The hybrid solution will see to it that the system will have the benefit of the flexibility of additive manufacturing and the accuracy of the conventional engineering components.

Table 1: Conventional Components Used

Sr. No.	Component Name	Purpose
1	Bearings	Reduce friction and enable smooth rotation
2	Bolts & Nuts	Assembly and fastening
3	Aluminium Bars	Structural rigidity
4	Motor	Provides rotational input
5	Pulley & Belt	Power transmission
6	Battery	Power supply

Material Selection for Additive Manufacturing

The choice of materials is important in influencing the performance of the 3D printed gyroscope. It has to be strong enough, durable and stable enough thermally and must also be usable with the printing process selected. A comparative analysis of the materials available has been conducted to settle on a decision to use the PLA PRO+ as a suitable material to make structural components. Increases in impact resistance and tensile strength have better mechanical characteristics than ordinary PLA with increase in impact resistance and tensile strength. These qualities make it suitable in parts that are subjected to moderate mechanical forces. Moreover, its increased thermal resistance enables the material to retain its structural integrity when subjected to different environmental factors.

The other significant advantage of PLA PRO+ is that it has a superior level of adhesion of its layers and consequently this means that it is less prone to delaminating as it is used. This is most important when it comes to the case of gyroscopic systems, which have cyclical stresses and vibrations. Furthermore, the material is biodegradable and is also made out of renewable resources

which makes it an environmentally-friendly alternative to additive manufacturing. In the case of rotor, the most important part in terms of dynamics, high-density materials like steel or aluminum are used. Gyroscopes can only work well on the basis of their angular momentum that is dictated by the mass and the speed of rotation. The higher the concentration of the rotor the higher the moment of inertia, which is more stable and resistant to external factors [13].

Assembly of Gyroscope System

Integration of the 3D printed components with the standard mechanical components to give a complete system of the gyroscopes will be done in the assembly process. This is initiated by attaching bearings in some of the housings that will have only minimal friction and a smooth rotation. Bearings are very important in stability and minimization of energy wastage during the course of operation [13]. Rotor assembly is then fixed to the central shaft and connected to the drive mechanism, often through a motor which is attached through a pulley and belt system. Eccentric movement and vibration should be prevented by aligning the rotor. Gimbal rings then are attached and at this point the gimbal is free to move in various directions and the gimbal can now respond dynamically to external disturbances. The structure is attached using fasteners (bolts and nuts) and attention is not paid to tightening it so much that it will deform the 3D printed components. Printed and traditional components are verified with interfaces to ensure sufficiently good contacts and load distribution. The final gyroscope system is presented in Figure 5, especially focusing on the integration of the structural components, rotor and drive mechanism. The image depicts the functionalization and compactness that additive manufacturing has enabled.

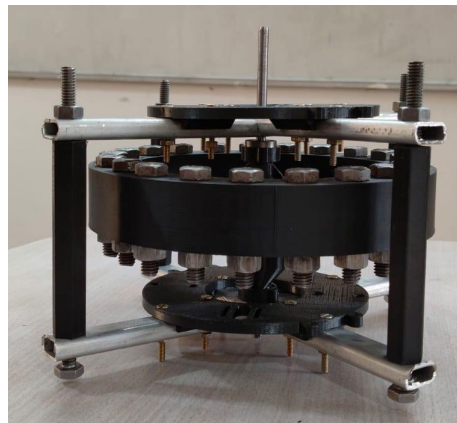


Figure 5: Fully assembled 3D printed gyroscope system integrated with conventional components.

Rotor Balancing, Calibration, and Quality Assurance

Balancing and alignment of the rotor is very important in the performance of gyroscopes because an imbalance in mass will cause undesirable vibrations which decrease the accuracy of the gyroscopes and may also lead to mechanical damage. Dynamic balancing is a technique that provides a uniform distribution of the mass around the axis of rotation by detecting the locations of heavy points and taking corrective action like removal of material or addition of a counter weight. This cyclical process is repeated in a cyclic manner until one attains stable rotational behaviour. Meanwhile, it is important to carefully align gimbal system to exclude parasitic torques which can disturb the gyroscopic effect and destabilize the angular momentum vector [9]. After assembly, the process of calibration and testing is carried out to provide a stable functioning under the changing conditions. Zero-rate calibration determines the baseline output when the gyroscopes are at rest, enabling to compensate the inherent biases [18]. The scale factor calibration establishes the correlation between the output and the actual angular velocity, which is important to ensure the accuracy of the measurements. Compensation methods are also used to reduce the effects of

temperature to ensure that the performance remains constant [17]. Dynamic testing provides rotational inputs and orientations to the system to test sensitivity, stability, and repeatability [19]. Quality assurance and process monitoring are incorporated in the entire manufacturing and assembly. Warping, separation of layers and dimensional errors in the printed components are detected and mitigated. Inspection, checking of alignment and testing of functioning at every stage will help to spot the problems in its early-stage and ensure the reliability and best possible operation of the system.

Results & Discussion

Additive manufacturing was used to develop the spinning-mass gyroscope; 3D-printed components were incorporated with more traditional mechanical components to test functionality, structural integrity, and cost-effectiveness. The process of fabrication, assembly, and calibration showed that this approach of hybrid was feasible. The prototype was able to prove the principle of conservation of angular momentum since it retained a constant orientation throughout operation. The rotor maintained its axis of rotation even under external disturbances like base tilting, as expected, the rotor behaved in a gyroscopic manner. The PLA PRO+ material used minimized the total system weight but retained adequate rigidity to increase handling and assembly. Moreover, dimensional accuracy of additive manufacturing made the fit of the components appropriate, minimized friction, and enhanced rotational stability. Dynamometer tests indicated good performance at moderate rotating speeds. High density rotor provided enough moment of inertia to allow motion to occur in a steady manner. However, high frequency vibrations were also recorded since small imbalances and inherent limitations of polymer-based components were also present, as with the earlier studies [13], [21]. Measurement consistency was checked by calibration of the low zero-rate offsets and a linear relationship between the output and the angular velocity. Effects due to temperature were smaller and could be removed with simple procedures [17], [18].

The study observes that additive manufacturing is characterized by the fact that it is able to create complex geometries without wasting a lot of material and without going through a lot of assembly processes [20]. A successful strategy to overcome the material limitations without affecting the performance was the hybrid design which involved the use of printed components with metallic rotors and precision bearings. According to the comparative analysis (Table 2), 3D-printed gyroscopes are cheaper, can be produced in a shorter period, and are more designable. Nevertheless, systems that are traditionally made still have a better precision and mechanical strength because of superior material properties and closer tolerances. In general, additive manufacturing is a possible and effective solution to the need to create lightweight, cost-effective, and customizable gyroscopic systems.

Table 2: Comparison Between Conventional and 3D Printed Gyroscopes

Parameter	Conventional Gyroscope	3D Printed Gyroscope
Manufacturing Cost	High	Low
Weight	Moderate	Low
Customization	Limited	High
Precision	High	Moderate
Fabrication Time	Long	Short
Material Efficiency	Low	High

Conclusion

This paper shows how a spinning mass mechanical gyro has been designed and fabricated successfully through additive manufacturing. The combination of 3D printing components and traditional mechanical components offers a moderate solution that makes the best of both technologies. The system created is capable of recreating the basic functionality of a gyroscope,

which proves the viability of additive manufacturing to be used as a gyroscope. PLA PRO+ material allowed to produce the lightweight and structurally stable components, and the use of high-density rotors and preciseness bearings provided the reliable work. The manufacturing procedure was cost-effective, flexible, and well-suited to the fast prototyping of a product and was thus a promising solution to educational, experimental, and low-cost engineering tasks. Research in the future ought to be conducted on improving the mechanical performance of the 3D printed gyroscopes with the help of superior materials like the fiber-reinforced composite and metal additive manufacturing. Enhancements in printing resolution and surface finishing methods can also minimize the losses during friction as well as enhance accuracy. The incorporated sensors and embedded control systems can also turn the developed gyroscope into a smart device that has the ability to monitor and provide feedback in real-time. Design efficiency and system performance can also be further enhanced by using optimization techniques, such as artificial intelligence and machine learning.

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