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Gyroscope

Sensor Physics 2025

08.05.2025

Smart IoT

Document history

Topic: Gyroscope

Project team: Bit Bot

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Course: Sensor Physics

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Version history:

|  |  |  |  |
| --- | --- | --- | --- |
| Date | # | Editors | Changes/Notes |
| 27.4.2025 | 1 | Binchi, Riina, Sheng, Zhiyong | Completed first-round research and evaluation |
| 03.05.2025 |  | Binchi, Riina, Sheng, Zhiyong | Second draft |
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# Introduction

The purpose of this document is to track and document the team’s collaborative inquiry into a sensor selected for investigation. This collaborative inquiry is part of the Sensor Physics course, which belongs to the study path of Smart IoT Systems major.

The document begins by presenting the chosen sensor and explaining the reasoning behind its selection. The team presents their initial knowledge and assumptions of how the sensor works. An evaluation of the initial knowledge is then performed to narrow the scope of research into areas requiring further research. After research, the team documents their findings in their own words, using proper referencing and graphics to illustrate their findings. The first cycle of collaborative inquiry ends with a summary of the round, and then the cycle will be repeated a second time.

In the second cycle, the team will base their research questions based on findings from the first cycle, deepening their understanding of the chosen sensor and its working principles. The team will again produce their own explanations for the research questions and then fill in any gaps by researching the topic from different sources. Finally, a summary of the second round will be written.

# The context

During the team discussions, we considered several types of sensors including pressure sensors, image sensor, light sensor and gyroscope. Each of these sensors plays an important role and has a variety of applications in different kinds of devices.

Each of us expressed our interests and reasons. We excluded sensors that were required in our IoT project and focused on those we are less familiar with. Through the process we had a shared interest in the gyroscope and agreed to select it as our study subject.

We are interested in gyroscopes because one of our candidates, the IoT project, involved motion detection using gyroscope and accelerometer. Although we didn’t select that project, we still have an interest in it and want to learn about how it works, especially gyroscopes. Also, in a previous course, we have done an experiment using accelerometers in our phone to measure the floors traveled in an elevator. That experience let us develop a further interest in gyroscopes and how they measure rotation.

# The first research question

How does it work?

# The first explanations

Based on what we observed in daily life and our initial discussion about how a gyroscope works, we believe it is fundamentally a movement-based sensor that generates angular momentum when it moves. We know that the internal mechanism consists of two main components: a "floating" part that's loosely connected to a "fixed" part. As the sensor moves, the floating component either pushes or drags against the fixed component, creating a physical effect that's then converted into measurable electronic signals.

We've considered several possible mechanisms for this conversion. One guess is that the moving parts alter their position in response to movement, generating either voltage or current changes that can be measured. Another theory assumes that there is a magnetic field generated inside the sensor, and the moving component interacts with this field differently as its position changes. Another assumption is that the sensor might contain a small tube with liquid that shifts with position changes, similar to how a spirit level works.

# Critical evaluation and learning objectives

Our initial research results shows that we understand the structure and purpose of traditional gyroscopes, and we have a certain understanding of the basic physics, such as angular momentum and motion state. However, we do not clearly understand the structure and the circuit-level mechanisms of the gyroscopes, as well as the ways to implement them in an embedded device.

For the next stage of the research, we need to investigate several key areas. First, we need to study the physics principles behind gyroscope sensors and find out whether there are different types of gyroscopes based on different mechanisms. Second, we should investigate how the sensor converts physical movement into electronic changes, specifically how does the sensor transfer angular motion into measurable voltage or current signals. Third, we need to determine whether gyroscopes use a single component to sense both angular position and movement, or if they consist of multiple components. Additionally, we need to understand how these gyroscope sensors are integrated into embedded IoT devices: what interfaces they use, how the data is processed by microcontrollers, and how they're calibrated for accurate readings. Finally, we should explore their practical applications in embedded systems, such as how they work alongside other sensors like accelerometers in motion-sensing applications.

# Search results

Gyroscopes are devices that attach to a frame and sense an angular velocity when the frame rotates (Passaro et al., 2017). There are many types of gyroscopes, each featuring its own operating physical principle. In this research, we mainly discuss three types of gyroscopes: mechanical gyroscopes, optical gyroscopes, and MEMS gyroscopes.

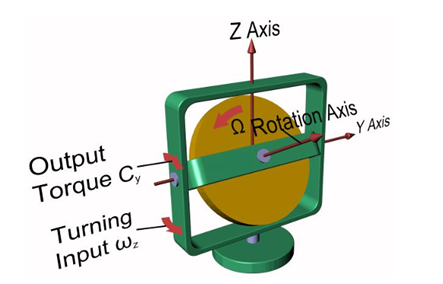
Mechanical gyroscope consists of a spinning mass rotating around its axis. A spinning mass has two properties. Firstly, it tends to maintain its position in space and resist forces that try to change the rotation axis. Secondly, when a force is applied on the mass, it moves perpendicular to the force. As shown in the diagram below, the input rotation ω exerted on the spinning plate creates an output torque around the Y axis. A mechanical gyroscope senses rotation by detecting and measuring this perpendicular force. (Passaro et al., 2017)

Figure 1: Physics principle of mechanical gyroscope

Optical gyroscopes are based on a physical phenomenon called Sagnac effect. When two light beams travel in opposite directions along the same circular path, if the system is stationary, the two beams will finish traveling through the path at the same time. When there’s rotation, on the other hand, there will be a phase difference when the two beams meet: the beam traveling in the direction of the rotation will travel a longer path, and vice versa.

Two of the commonly used optical gyroscopes are the Ring Laser Gyroscope (RLG) and the Fiber Optic Gyroscope (FOG). RLG consists of a closed-loop path (usually triangle or square) with mirrors at the corners. The sealed cavity is filled with gas that can produce laser light when energized. The light travels in both directions and the rotation of the device will produce a frequency change that can be measured. FOG uses optical fiber coils where the light beams travel in opposite directions, which produces a phase shift when undergo rotations.

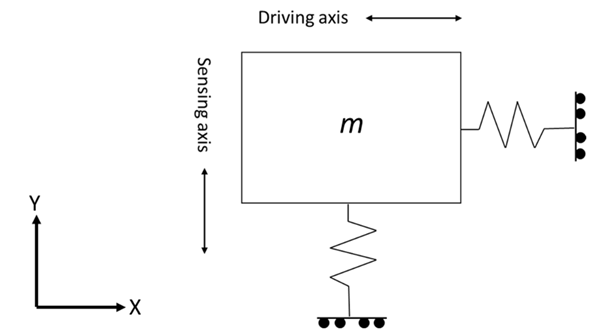
MEMS (Micro-Electro-Mechanical Systems) gyroscopes are tiny motion sensors that detect rotation. The core principle behind it is called the Coriolis effect, which states that if a moving mass undergoes an angular velocity, the mass will experience a force that is orthogonal to the moving velocity and the angular velocity.

Figure 2: Coriolis effect in MEMS gyroscope

This simple diagram depicts the basic principle of a MEMS vibrating gyroscope. The mass m continuously vibrates along the driving axis X. When the system rotates along the Z axis, the angular momentum creates the Coriolis force in the direction of the sensing axis Y, which triggers a new vibration that can be detected and measured (Gill et al., 2022).

Coriolis force can be measured in different ways. One way to measure Corolis force is using capacitive sensing. Where two electrodes on opposite sides of vibrating mass make a capacitor. Corolis force moves mass causing the distance between electrode plates to change, which changes the capacitance. This change of capacitance then can be measured and converted to angular velocity (Gill et al., 2022).

Another way that Coriolis force can be measured is with Piezoelectric sensing. Where certain materials generate small voltage when it is mechanically bent. When Corolis force bends the structure, it creates stress on piezoelectric elements, which creates a small voltage signal. That signal can be amplified and converted to angular velocity (Gill et al., 2022).

Modern smart devices such as phones use inertial measurement units (IMU) to measure angular position and movement. The IMU typically consists of multiple sensors including gyroscope, accelerometer, and magnetometers. However, it is important to note that gyroscopes are specifically designed to measure rotational motion rather than movement. Whereas the accelerometer is the translational motion sensor that detects linear acceleration. (Gill et al., 2022)

We selected three commonly used digital gyroscope sensors: MPU-6050, L3GD20H, and BMI270, which are used in consumer electronics, industrial applications, and wearable devices respectively. According to the datasheets, MPU-6050 supports I²C only, while L3GD20H and BMI270 support both I²C and SPI interfaces. All three sensors integrate an ADC and an on-chip FIFO buffer to temporarily store angular rate data. The microcontroller receives a data-ready signal via an interrupt, then reads data from the FIFO through the I²C or SPI interface. The FIFO size is specified as 1024 bytes for MPU-6000/6050, 32 levels of 16-bit data for L3GD20H, and 2 KB for BMI270. For calibration, the MPU series provides a user self-test function to verify the functionality of each axis. L3GD20H is a factory calibrated at 3.0 V, with no mention of user-accessible calibration. BMI270 includes fast offset error compensation and fast sensitivity error compensation, reducing gyroscope sensitivity error to a typical 0.4%. (Invensense, 2013; STMicroelectronics, 2013; Bosch Sensortec, 2023)

# Summary of the first round

Through our investigation, we identified three types of pf gyroscope and the physics behind them: mechanical gyroscopes, optical gyroscopes, and MEMS gyroscopes. Focusing on the MEMS gyroscopes, we researched the measurement methods and investigated the datasheet of certain modules produced by mainstream manufactures.

This research effectively answered our initial questions about gyroscope types, operating principles, and practical implementations. We met our objectives by gathering information from reliable academic sources and module datasheets. The technical data we collected provides a solid foundation for the next stage of our investigation.

# New questions

When researching how gyroscopes work, we found that there are many different types of gyroscopes. This led to our first question: How accurate are different gyroscope systems?

Since we study embedded systems, we are particularly interested in MEMS gyroscopes, as they are small and often used in embedded devices. This raised another question: How is MEMS gyroscopes made so compact while keeping the cost low?

The core principle behind MEMS gyroscopes is the Coriolis effect. We know the phenomenon, but it led us to ask: Where does the Coriolis force come from? Why does it exist?

# The second explanation

We made assumptions about the gyroscope internal construction, measuring way, material, and manufacture technics.

We assume the core of the gyroscope contains a small piece of quartz-like material. It can receive different vibrates from different directions and uses sensing elements to measure them.

Another assumption is that there is a kind of thin film material in the core of the gyroscope. Its internal part might be driven to vibrate by an external electrical signal.

When the gyroscope is rotating, the sensing element would measure additional vibration to obtain the rotation angle or angular velocity.

In our opinion, the gyroscope construction should be as simple as possible and capable of measuring rotational data accurately.

For cost reasons, we assume the manufacturer uses special materials to make the gyroscope, such as quartz, silicon, and so on.

Given that integrated circuits can be manufactured on a large scale, we speculate the degree of gyroscope manufacturing difficulty is like that of integrated circuits, So, we guess the gyroscope also uses similar techniques to reduce cost.

We conclude that gyroscopes combine simple construction, special material and IC-like manufacturing techniques to achieve small size and low cost.

# Critical evaluation and learning objectives

After our previous research and reading articles about MEMS gyroscopes, we have gained a basic understanding of their fundamental components and structure. For how they are made compact, we considered materials, structure, and manufacturing, and suggested several ways they might vibrate. However, our explanation has limitations, as we only focused on part of the question, such as the vibration aspects, while lacking a full understanding of the whole system. We didn't explain well how they are made small and accurate while keeping costs low.

To fill these gaps in our research, we need to focus on several key areas: First, we need to learn more about the materials used in MEMS gyroscopes and why they are chosen, including how these materials affect how well they work and whether they are expensive. Second, we need to study the inner design details, especially how they can measure rotation accurately at such a tiny scale while keeping the structure reasonably simple. Third, we need to understand exactly how the vibration is created and how it works. Finally, we need to study the manufacturing process in detail, especially whether it uses the same or similar technology as integrated circuits to achieve mass production at low cost. We should read technical papers, reports, and documentation from manufacturers to learn more about how MEMS gyroscopes are designed and made.

# Search results of the second round

Instructions: Share your personal search results here. Try to answer your learning objectives. Search from internet, MetCat library search engines, books, articles, etc.

There are several MEMS gyroscopes designs that work effectively despite their tiny size. For example, the tuning fork design features two miniature masses vibrating in opposite directions, which cancels out external vibrations and provides clean signals despite the microscopic dimensions. The ring design uses a circular structure supported by eight tiny springs connected to a central anchor, with the symmetrical arrangement providing stability at microscale. The radius of a high precision vibrating ring structure was as small as 1.35 millimeter and the thickness of the structural layer was only 150 micrometers (Gill et al., 2022).

# Summary of the second round

Instructions: Discuss and summarize the latest information. Evaluate how well you achieved your learning objectives

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