Microrobotics

Prof. Palani Iyamperumal Anand

Department of Mechanical Engineering

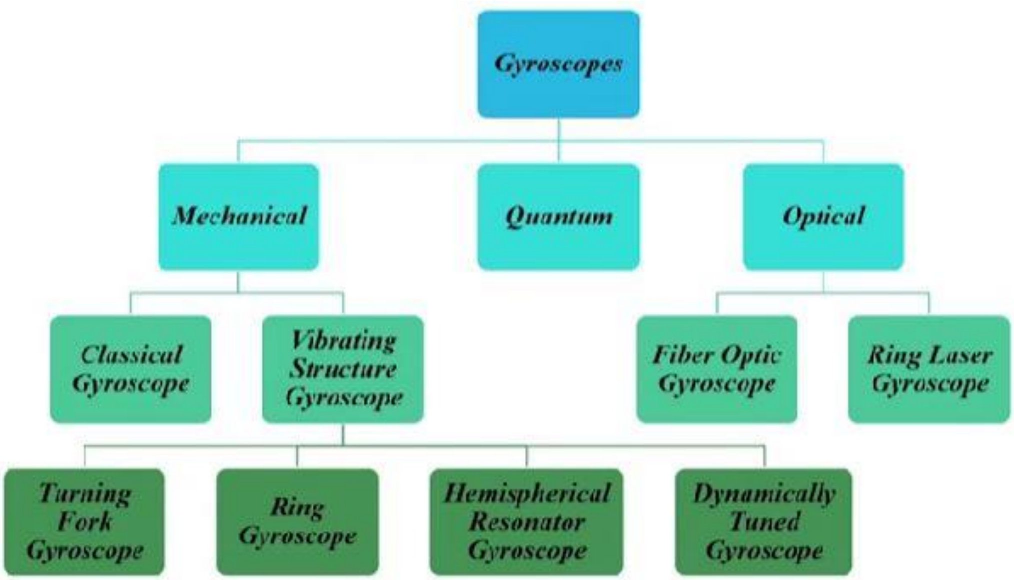
Indian Institute of Technology, Indore

Week- 07

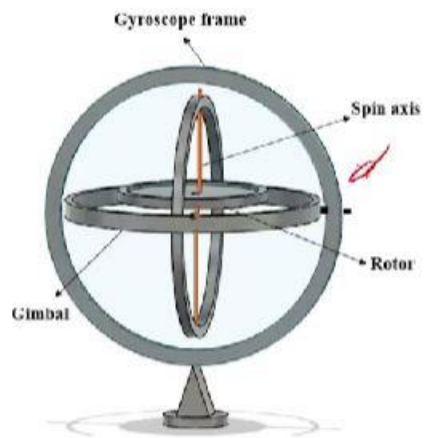
Lecture No- 31

Micro Sensors and Micro Transducers - Module 06

Last week's lecture we discussed micro sensors and micro transducers. We discussed the different sensing elements, transduction elements, and the optomechatronic systems, as well as the different modes of optomechatronic systems and how optical fibers are used for micro sensing and micro transduction. This week we will discuss gyroscope accelerometers, mechanical switches, flow transducers, haptic interfaces, and sensory skin for micro robotic systems. Let us discuss the micro gyroscope accelerometers first. The term gyroscope conventionally referred to the mechanical class of gyroscopes, which is derived from the ancient Greek language, being the physics of precession motion (slow movement of the axis of a spinning body). They are also named gyros, which are used to measure the angular rate around a fixed axis with respect to inertial space.

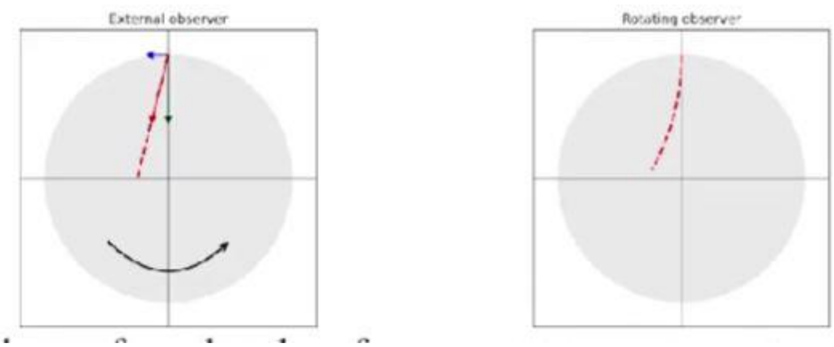


The gyroscopes can be classified based on the domain, i.e., mechanical domain, quantum domain, and optical domain. The mechanical domain is classified into two: one is called a classical gyroscope, and the other is called a vibrating structure gyroscope. However, in the case of an optical-based system, we can classify it as a fiber optic gyroscope or a ring laser gyroscope. Also, the vibrating structure gyroscopes are classified into four categories: tuning fork gyroscope, ring gyroscope, hemispherical resonator gyroscope, and dynamically tuned gyroscope. Now, considering the classical mechanical gyroscope, it consists of a spinning wheel or disc, also known as the rotor, mounted on a frame. The frame, which allows for freedom of movement in two or three planes, comprises a gimbal system. The basic principle behind a gyroscope is the conservation of angular momentum, a property that states that a spinning object will continue to spin about its axis unless acted upon by an external torque.



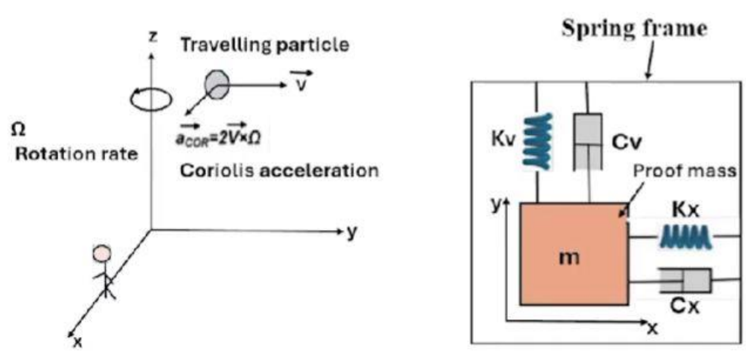
When the rotor spins at high speed, the gyroscope exhibits two main properties: rigidity in space and precession. This rigidity in space refers to the gyroscope's ability to maintain its orientation in relation to fixed points in space. So, the precession, on the other hand, occurs when an external force is applied to the gyroscope, causing it to change its orientation at a right angle to the direction of the applied force. The application of the classical mechanical gyroscope includes navigation systems in ships, aircraft, and spacecraft, gyrocompasses for determining true north, inertial guidance systems in missiles and satellites, and stabilization of large boats and cameras. These gyroscopes are advantageous as they exhibit high accuracy for detecting rotational motion.

They also provide stability and maintain directions in moving objects. However, it can be noisy compared to modern alternatives. It also deals with mechanical wear over time and has a larger size compared to the MEMS gyroscope. The overall construction of the gyroscope includes a gyroscope frame, a spin axis, a rotor, and a gimbal that takes care of the entire functionality of the gyroscope. Now let us discuss the vibrating structure gyroscope.



The working principle of vibrating structure gyroscopes, also called Coriolis vibratory gyroscopes, is based on the Coriolis effect. The Coriolis effect refers to the generation of an imaginary force perpendicular to the moving direction of a subject within rotating coordinate systems. These vibrating structures, gyroscopes, utilize the Coriolis effect to convert the rotary motion of the subject into a measurable linear motion. The figure shows the trajectory of a ball thrown from the edge of a rotating disc as seen by an external observer; because of the rotation, the ball has both an initial tangential velocity and radial velocity given by the thrower. These velocities bring it to the right of center.

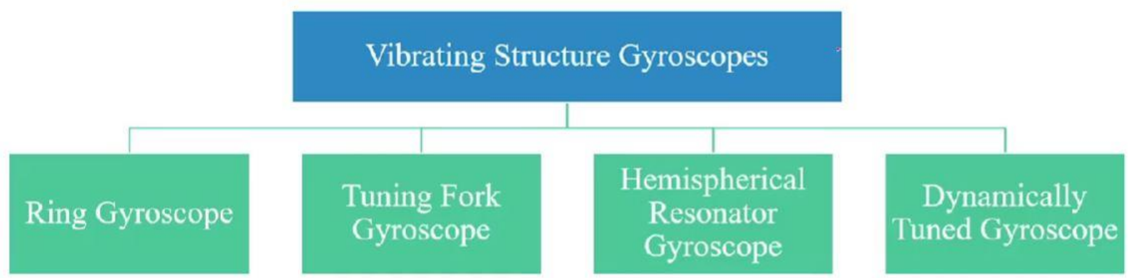
Similarly, in the right figure, the trajectory of the ball thrown from the edge of a rotating disc, as seen by the rotating observer, is deviating from the straight line as shown. Now imagine that an observer sitting on the x-axis of a rotating coordinate system around the z-axis observes a moving particle traveling at the velocity v in space. Because of the rotating coordinate system, the particle has a trajectory towards the x-axis with an acceleration of 2V*ohm from the observer's point of view. This apparent acceleration observed in a rotating coordinate system is called the Coriolis acceleration, proportional to the rotation rate of the coordinate system and the traveling velocity of the object v. According to this phenomenon, a gyroscope without any rotary parts can be designed that consists of two sets of mass-spring-damper systems positioned in a perpendicular direction, as shown in the figure.



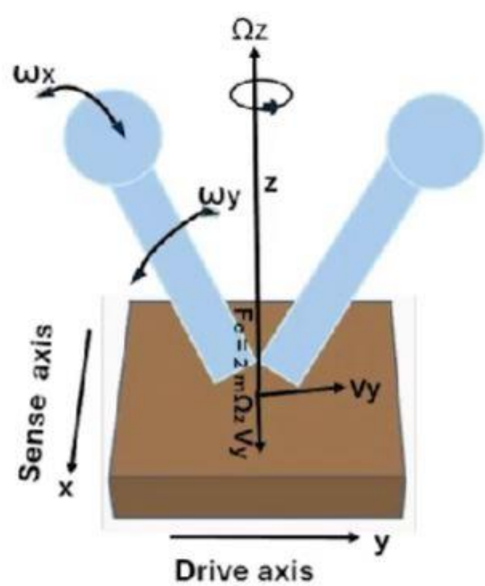
(a) illustration of Coriolis effect; and (b) the mass-spring-dasher system of a vibratory gyroscope.

Figure (a) shows a traveling particle along the Coriolis acceleration, and figure (b) shows the proof mass, which is being kept with a spring and damper arrangement depicting the system of a vibratory gyroscope. The main advantage of such kinds of gyroscopes is that they are compact and lightweight, with no moving parts except for vibration, which increases their reliability. It has low power consumption, which makes it suitable for MEMS technology, enabling mass production. Limitations include a gradual output deviation over time, reducing long-term accuracy. External shocks and vibrations disrupt measurement accuracy.

Their performance varies with temperature changes, requiring compensation. They are useful in consumer electronics, particularly in smartphones and gaming controllers. In automotive applications, they are used for stability control systems. They are also used for navigation in aircraft and spacecraft. In robotics, they perform motion sensing and control.

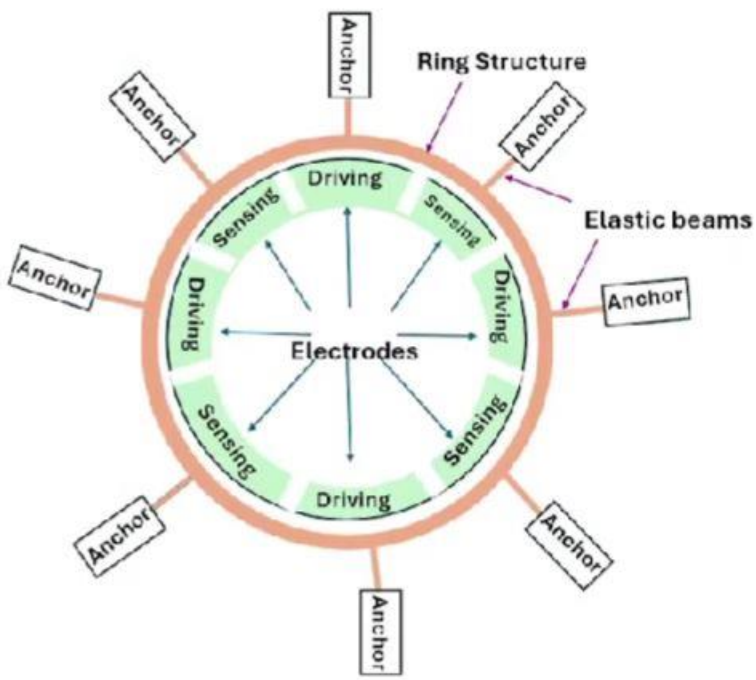


Now, considering vibration structure gyroscopes, they are classified based on their functionality as ring gyroscopes, tuning fork gyroscopes, hemispherical resonator gyroscopes, and dynamically tuned gyroscopes. Let us first discuss the tuning fork micro gyroscope accelerometer. They consist of two parallel beams of tines that vibrate in opposite directions. In drive mode, the tine oscillates in a plane, typically in the xy plane. In sense mode, an out-of-plane vibration (z-axis) is caused by the Coriolis force when rotated.

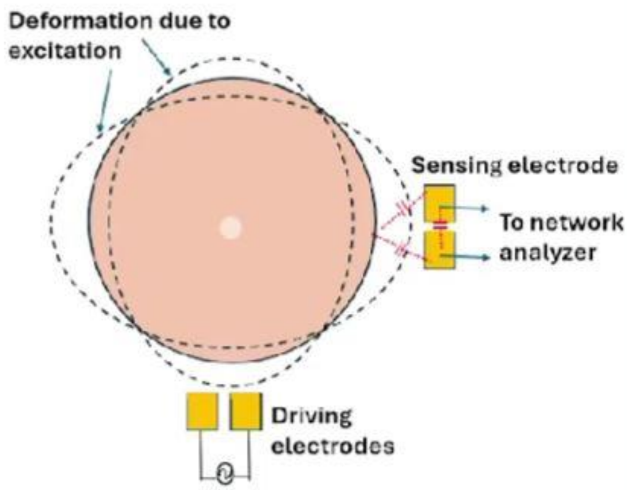


The tines are typically driven at their resonant frequency using electrostatic or piezoelectric actuation. When the gyroscope experiences angular rotation, the Coriolis effect causes a secondary vibration orthogonal to the drive motion, which is detected to measure the rotation rate. The major advantage is that the differential operation cancels common mode noise and doubles the output signal. It has high sensitivity due to resonant operations and a compact size, which is especially useful in MEMS implementation. It also exhibits low power consumption compared to the other gyroscope types.

Next, let us discuss the ring micro gyroscope accelerometer. It has anchors, and there is a ring-like structure connected to the anchors, which is in the form of an elastic beam. It has an inner electrode and a sensing element. It consists of a thin ring suspended by support beams, with electrodes around the ring for actuation and sensing. The ring vibrates radially in its primary mode.



When rotated, the Coriolis force causes deformation in the orthogonal mode. The magnitude of this secondary vibration is proportional to the angular rate. The major advantage of ring micro gyroscope accelerometers is that they are compact in size, especially in MEMS implementation. They exhibit low power consumption, are suitable for integration into various devices, and can detect around multiple axes with a single structure. Next is the hemispherical resonator microgyroscope accelerometers.

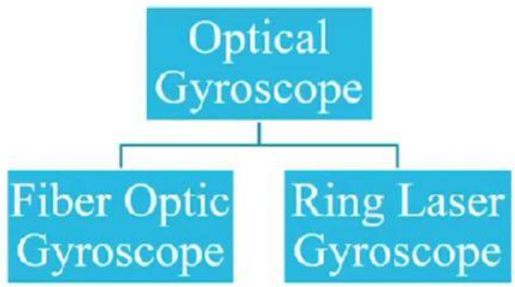


The gyro shell is subjected to external excitation, which leads to deformation. This excitation is analyzed using a network analyzer, which acts as a sensing electrode, and there is a driving electrode that provides the vibration to the shell. A hemispherical resonator gyroscope is also known as a wine glass gyroscope or mushroom gyro. It is a high-performance angular rate or rotation sensor with no moving parts. It has a thin solid-state hemispherical shell anchored by a thick stem, the shell driven to flexural resonance at its natural resonant frequency by electrostatic force from the surrounding electrodes.

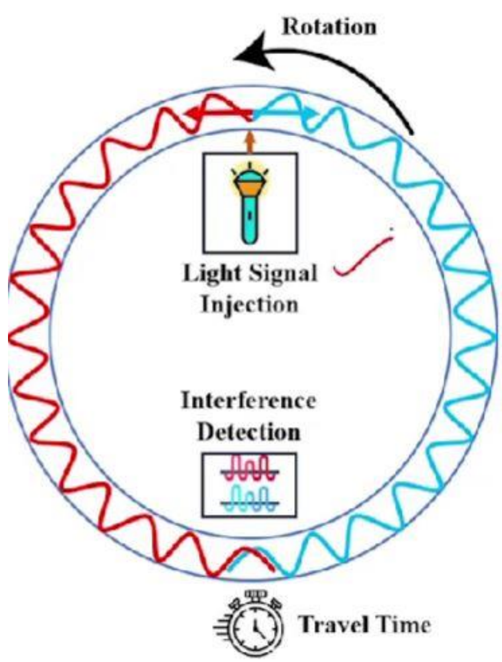
This utilizes the inertial properties of flexural standing waves for the gyroscopic effect. When subjected to angular rotation, the Coriolis effect causes the standing wave pattern to rotate relative to the resonator. So the amount and direction of this precession are directly proportional to the angular velocity of rotation. The key advantage of hemispherical resonator micro gyroscope accelerometers is that they are highly accurate and insensitive to external perturbations. They are superior in size, weight, and power characteristics.

It generates no acoustic or radiated noise. Radiation-hardened fused quartz material is used. Ultra-low angular random walk and power dissipation. Now we will discuss the dynamically tuned microgyroscope accelerometers. They have a high-precision angular rate sensor used in inertial navigation and guidance systems.

It consists of a rotor supported by a flexible joint with two pairs of orthogonal torsion bars and a balancing ring frame. The rotor is driven by a spin at a high speed of over 10,000 rpm by a miniaturized motor. It uses a negative elastic moment from dynamic effects to offset the positive elastic moment of the torsion bars. It operates in a free rotor state without torque and improves the gyroscopic precision. From an advantageous perspective, it is suitable for applications that require precise measurements in challenging environments. It has high accuracy, a wide dynamic range, and low drift. It is applicable in aviation and spacecraft navigation systems, marine navigation systems which include ships and submarines, missile guidance systems, oil field exploration and development systems, and robotic and autonomous systems. Now, let us discuss these quantum gyroscopes. The quantum gyroscopes are highly sensitive devices that measure angular rotation based on quantum mechanical principles, particularly the Josephson effect and quantum interference. Now, these optical gyroscopes, which are nothing but quantum gyroscopes, can be classified into two.



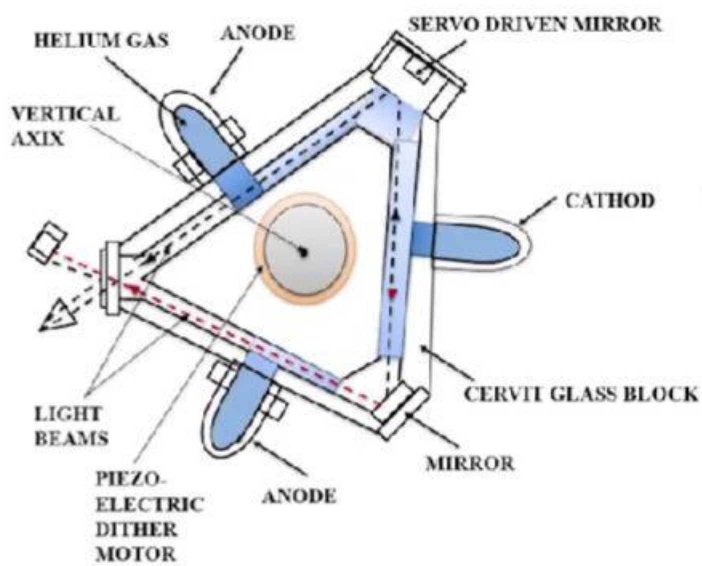
One is called a fiber optic gyroscope, and the other one is a ring laser gyroscope. First, consider the fiber optic micro gyroscope accelerometers. They are highly precise sensors that measure angular velocity using the Sagnac effect. In the given construction, two important processes come into the picture. One is the light signal injection, and the other one is the interference deduction.



Rotation is provided to the setup for analyzing the parameter. It consists of two laser beams that are injected into opposite ends of a long optical fiber coil. When the fiber optic gyros rotate, the beam traveling against the rotation experiences a shorter path delay. The resulting phase shift is measured through interferometry. The phase shift is proportional to the angular velocity.

The key advantage of these particular fiber optic gyroscope accelerometers is that it doesn't have any moving parts, so it doesn't have any impact on the system on which it is mounted. It has increased reliability and lifespan, high accuracy and stability, immunity to electromagnetic interference, a wide dynamic range, instant startup, and is compact and lightweight. They have applications in inertial navigation systems for aircraft, ships, and submarines, altitude control in spacecraft and satellites, the oil and gas industry for directional drilling, robotics and autonomous vehicles, and military systems for targeting and stabilization.

Next are ring laser micro gyroscope accelerometers. They are high-precision devices used to measure angular velocity based on the Sagnac effect. Construction of this gyroscope includes the laser beams, helium gas, and then the electrodes are placed in a particular orientation. There is a piezoelectric diether motor and a servo-driven mirror in place to guide the laser appropriately. The working principle of the ring laser micro gyroscope accelerometers includes two laser beams that are generated to travel in opposite directions, i.e., one is in the clockwise direction and the other one is in the counterclockwise direction within the ring cavity filled with a gaseous medium such as helium neon.

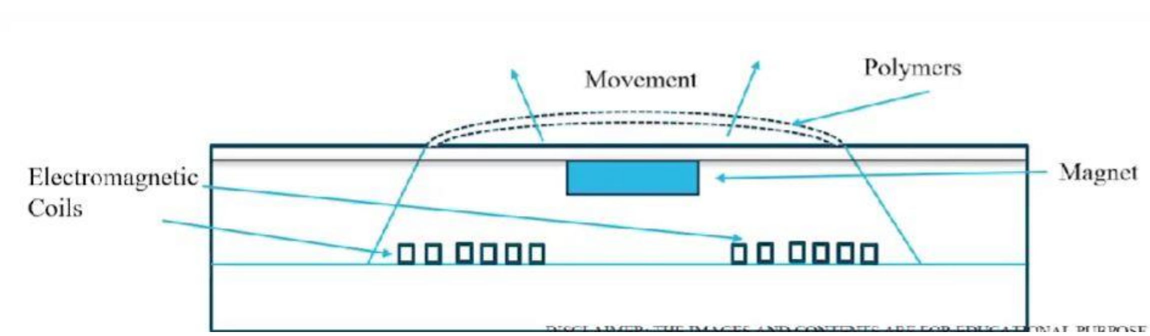


These beams form two independent resonant modes over the same optical path. The frequency difference is measured to determine the angular velocity of this particular system. Its advantages are that it also doesn't have any moving parts, which increase its durability and reliability. It has high accuracy and precision. It has a compact and lightweight design. It has instant startup capability and is resistant to high g-forces and vibrations. They are applicable as inertial navigation systems for aircraft, ships, and spacecraft, as well as military systems for targeting and stabilization. They are also useful in autonomous vehicles and drones. The next part is related to micro-mechanical switches. Switches are mainly meant for controlling the displacement as well as the position.

So, if we need to reach a particular position, these switches can be effectively used to position our system based on our requirements or the characteristics. Now, the micro mechanical switches are basically meant to use a physical movement to make or break electrical connections. Switches include simple mechanical contacts to sophisticated micro-electromechanical systems. They're essential components in nearly all electronic devices and systems. The physical contacts between conductors control electric flow.

Technological progression has driven miniaturization and its enhanced capability. The figure shows a simple template of the micro mechanical switches. So, in this micro-mechanical switch, we have two electromagnetic coils, a polymer diaphragm, and a magnet. The magnet will have control over the movement frequency or vibration. These electromagnetic coils will be helpful in providing the required displacement.

The overall potential actuation is taken care of by these electromagnetic coils and a magnet. So, based on the movement of the magnet, the frequency as well as the vibration is controlled. The basic working principle is a physical contact operation between a conducting element and force application, which causes a displacement of a movable contact. The circuit completion occurs when the contact touches and allows the current to flow. The mechanical restoration is done through a spring or, in some cases, a diaphragm, so that the diaphragm itself will help bring about the mechanical restoration.

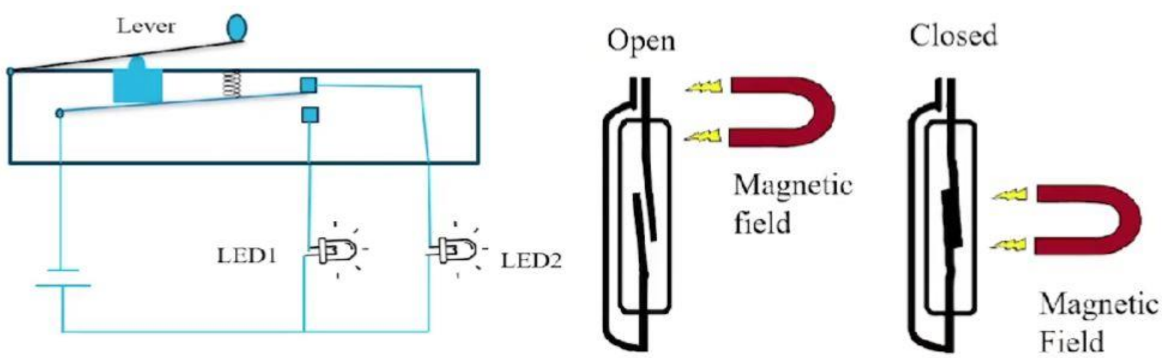


The materials are selected appropriately so that the mechanical restorations can be achieved. The key components are a fixed contact, a movable contact, an actuation mechanism, a restoring mechanism, and housing based on our requirements. There are two types of mechanical switches: one is called a reed switch, and the other is a micro switch. The reed switches are glass-encapsulated metal reeds that respond to the magnetic field. They have a non-contact activation through the proximity of the magnetic field.

The micro switches are small precision switches with a defined point and physical contact with the lever or button. Let us see the overall configuration of both switches. The figure shows a reed switch, which is operated by a magnetic field. This magnetic field is used for actuating these reeds.

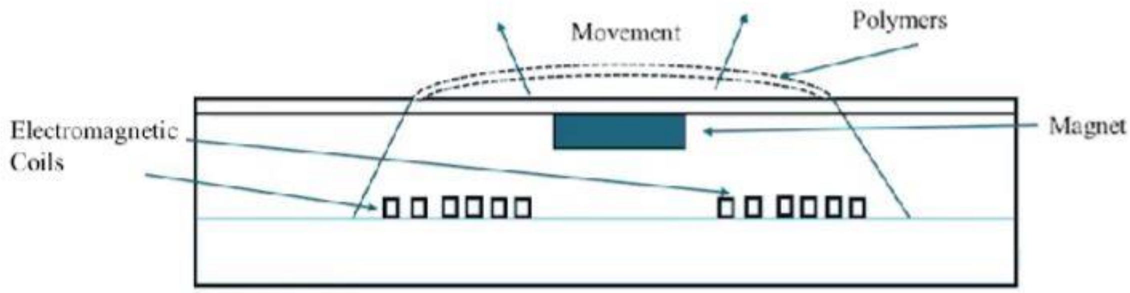
Initially, the switch is in an open state. If we apply a magnetic field to the switch, it comes to a closed state and facilitates current flow. When the magnetic field is switched off, the contact again returns to the open state and current flow stops.

Now in micro switches, we have a lever and a spring that are used to establish and remove the contacts. When the lever is pressed, it pushes the upper portion of the switch and, as a result, closes the switch. This completes the circuit and leads to actuation or LEDs glowing.



In both these conditions, the reed and the lever are used for controlling the sensing of the position, and they give out appropriate actions. Now we will discuss about the next configuration called as the membrane switches. These membrane switches comprises of thin flexible layers with printed circuit. The pressure creates a contact between the circuit layers. Now, this configuration we had already discussed where we have two electromagnetic coils, there is a magnet and a polymer membrane which moves to create contact.So this thin flexible layer will move back and forth due to magnet movement. It has a capability towards both actuation and sensing.

Next we have the snap action switches. These switches has a spring-loaded mechanism for rapid state change. So it provides a tactile feedback through a distinctive snap action.



It has a fixed base with an electrical coil attached to it. In certain cases either it might be a shape memory alloy spring or it might be a kind of a excited spring i.e. it has a coil . The electrical contact is attached to the free end of the spring or coil.

The movement of the SMA spring can be controlled by a heater. Due to heating the SMA spring expands and results in movement of electrical contact. In the case of a solenoid, we have a magnetic field. Here, the spring plays a vital role in controlling the overall action. We will discuss about this MEMS based switches in the upcoming lecture.