Sensors and Actuators

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Abstract Mechatronics engineering is a creative and dynamic field that focuses on cutting-edge technology for a variety of applications, which include high-speed manufacturing systems used in many contemporary companies. Modern manufacturing incorporates sophisticated technology, cutting-edge software, tools, and goods that improve quality of life by utilizing intelligent sensors and parameter controllers. In smart autonomous manufacturing, mechatronics has improved efficiency and product quality while decreasing technical faults. This chapter provides a detailed overview of recent mechatronics research with applications in manufacturing, agriculture, industrial automation, robotics, biomedical and assistive technology, human–machine interface, unmanned vehicles, energy, aerospace, and transportation. Production has significantly increased as a result of Industry 4.0, digitization, and artificial intelligence integration in mechatronics have significantly increased production. A significant factor in the change in the automobile industry has been the development of mechatronics in electric and driverless vehicles. Numerous research and development initiatives have the potential to advance the use of mechatronics, in line with forthcoming findings. Mechatronics-based technology encompasses nearly all aspects of intelligent industrial techniques and contributes to a high-quality lifestyle for almost everyone.

Keywords Sensor · Actuator · Digitization · Biomedical · Manufacturing

1 Introduction

Sensors and actuators are integral parts of a mechatronics system. Mechatronics has advanced in every aspect of contemporary or modern technology, from massive industrial systems to individual parts used in consumer products. Two of the most

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important parts of mechatronic systems are electromagnetic sensors and electromechanical controllers. Sensors as well as actuators in mechatronics design and applications provide a practical understanding of the characteristics and operations of various electromagnetic and electromechanical devices. Mechatronics or engineering systems use them to sense undetermined signals and perceive unknown parameters of their environment. In essence, sensors are required to gather data from the system and monitor it. This will support in controlling and operating the system. Various control equipment needs the use of control actuators. Some devices use both; for example, MEMS uses microminiature sensors and actuators. This chapter presents an introduction to sensors and actuators. This chapter delves into the functions and uses of several typical sensors and actuators in mechatronic systems.

2 Classification of Sensors

Figure 1 shows the classification of sensors. Generally, two categories of sensors are available: analog and digital. When necessary, ADCs can convert the analog output from analog sensors into a digital signal. Some analog sensors are potentiometers, DC tachometers, capacitive sensors, piezoelectric sensors, strain gauges, torque sensors, etc. Digital sensors produce digital output as their name suggests. Some digital sensors are shaft encoders, light sensors, Hall effect sensors, MEMS sensors, etc.

2.1 Analog Sensors

An analog sensor measures continuous physical parameters, data, or quantities and converts them into electrical signals. Various mechatronics systems utilize the working principles and applications of certain analog sensors.

2.1.1 Potentiometer

The potentiometer, also known as the angular potentiometer or the linear potentiometer, is a crucial sensor that measures angular or linear displacement. Since the potentiometer draws no current, it is useful for monitoring currents. By balancing the unknown EMF against known potential differences, a potentiometer circuit compares and measures potential differences [1]. Ambrose Fleming, the vacuum diode's inventor, used this approach to measure currents up to 500 A in 1885 [2–4]. Xiao Dong used a potentiometer in the vehicle steering system [5]. This steering system includes sensors that transmit signals to inform the car of the driver's desired wheel movements. It is likely for the motors in the steering system to give the driver feedback on the car's condition. This system provides a safe and friendly environment. In reality, the industry uses a digital potentiometer as a light-independent

Fig. 1 Sensor classification diagram

resistor. An LDR (light-dependent resistor) is an alternative to the thermistor since it is less susceptible to changes in temperature and humidity [6]. Figure 2 displays a schematic circuit diagram of a potentiometer.

In the schematic below,

R1 and R2 = Resistors of the pot.

V = voltage difference between the input and output pin.

RL = the resistance of the load (a motor or an LED), when a pot is turned, the values of the resistors are changed too. Moving the pot one way will reduce R1 and increase R2. This outcome in different voltage values on the wiper (the one that goes to RL in the schematics below).

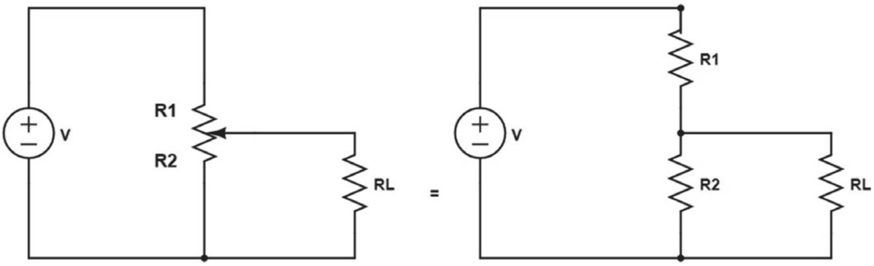

Fig. 2 A potentiometer schematic circuit diagram

$$V_L = \frac{R_2}{R_1 + R_2} \cdot V_s$$

where VL = voltage difference between the wiper and the output pin.

Potentiometers can control electrical signals and regulate resistance, commonly used in audio equipment like mixers, amplifiers, and guitars to regulate tone and volume [7].

2.1.2 Rotary Potentiometer

A rotary potentiometer, as shown in Fig. 3, adjusts the supply voltage to a specific portion of an electronic circuit. This potentiometer can adjust its resistance to electric current by rotating the knob or sliding the lever [8]. To determine the overall resistance, the rotary potentiometer consists of a resistive strip linked to terminals and a sliding contact connected to another terminal. By changing two resistances between three terminals 1, 2, and 3, the potentiometer acts as a regulator over these amounts or occurrences. This is done by the user moving its wiper. As shown in Fig. 3a, the maximum total resistance (RT) of an ideal potentiometer law is the sum of the resistances between terminals 1 and 3. Each terminal and wiper are regarded as ideal conductors, implying that they possess zero resistance [9].

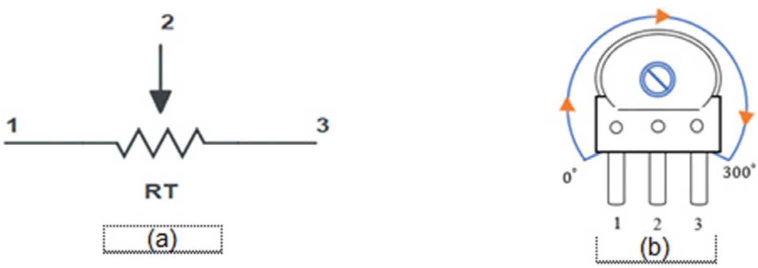

Fig. 3 **a** Potentiometer schematic symbol **b** Rotary potentiometer diagram with labeled terminals and the rotating shaft highlighted and range of rotation indicated, the shaft shown at 0°

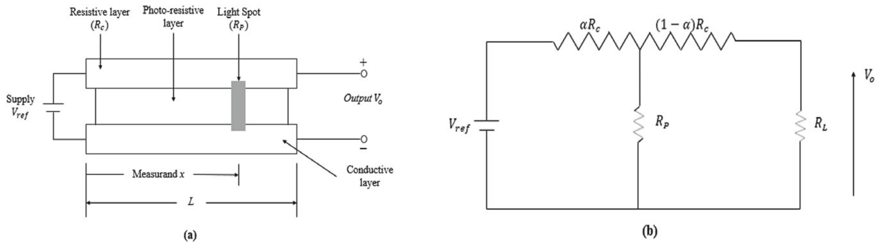

Fig. 4 **a** An optical potentiometer **b** Equivalent circuit (α = χ/L)

Many equipment functions use rotary potentiometers [10], including robotic hand control systems, stiffness readouts in musculoskeletal humanoid robots [11], volume control, and position sensors in motor control [12].

2.1.3 Optical Potentiometer

Optical potentiometers, or optical position sensors, are electronic devices that measure and control position or displacement [13]. An optical potentiometer uses a fluorescent optical fiber sensor to measure an object's position [14]. The potentiometer employed a fluorescent optical fiber with a track diameter of 1 mm. The optical cable was terminated by photodiodes with a p-i-n structure, while a light-emitting diode modulated at a frequency of 5 kHz was used as the excitation slider. According to Beer's law,

$$\mathrm{I(d)} = \mathrm{IOe} - \alpha \mathrm{d}$$

where I(d) is the intensity of light at any distance, d, from the detector, I is the constant multiplier intensity, and a is the attenuation constant [7]. The optical potentiometer, shown schematically in Fig. 4, is a displacement sensor. A layer of photo-resistive material sits between a regular resistive layer and a conductive layer [15]. In the following Figure, Rc = total resistance, Rp = Resistance of light projected area, RL = resistance of the load vref = Supply voltage of pot, and L = length of resistive layer.

Optical potentiometers are versatile devices that find applications in many industries and fields [16], especially for accurate measurement of displacements and velocities [17], as well as in robotics, medical fields, etc. [18].

2.1.4 DC Tachometer

A tachometer uses an analysis of the relative movement between the magnetic field and the shaft to determine the angular velocity, or rotational speed, of a machine. The velocity of the coils is precisely proportional to the speed of the shaft. This velocity induces an electromagnetic force (EMF) in the magnet's constant magnetic field. There are two varieties of tachometers on the market: electronic and mechanical. Compared to mechanical tachometers, the electrical tachometer provides more advantages by converting rotational speed into electrical voltage. The machine's shaft is connected to the DC tachometer generator, which measures the machine's speed. Some of the important parts of the DC tachometer generator are the moving coil voltmeter, brushes, armature, commutator, permanent magnet, and variable resistor. The DC tachometer operates by moving the conductor through a magnetic field, which induces an electromotive force (EMF). The conductor's magnetic flux and the shaft's velocity determine the magnitude of the induced electromotive force (emf). Brushes convert the force, proportional to shaft speed, into direct current. The voltmeter connects in series with the resistance to regulate the heavy armature current, while the induced voltage polarity controls the shaft motion. To measure speed, permanent-magnet transducers use electromagnetic induction between a permanent magnet and a conducting coil [15].

2.1.5 Capacitive Sensor

A capacitive sensor detects liquids or solids without physical contact. To detect these targets, the capacitive sensor's detecting end generates an electrical field. This sensor detects targets that interfere with the electrical field. Capacitors can detect paper, plastic, glass, cloth, and wood. A capacitor sensor detects oil, paint, water, etc. A capacitive sensor functions like a capacitor. This sensor connects a metal plate on the sensing face to an oscillator circuit, and the detected target becomes the capacitor's next plate. Capacitive sensors generate electrostatic fields, unlike inductive sensors. A capacitive displacement sensor is a type of capacitive sensor. Capacitive displacement sensors are contactless instruments that can accurately measure the position and movement of any conductive object with great precision. In addition, they have the capability to gauge the thickness or density of materials that do not conduct electricity [19]. Figure 5 shows two different architectures of capacitive sensing.

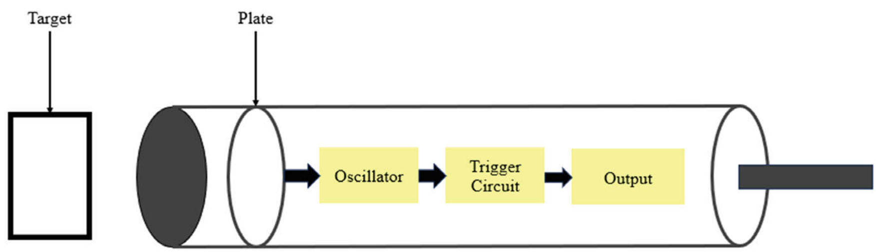

Fig. 5 Capacitive sensor

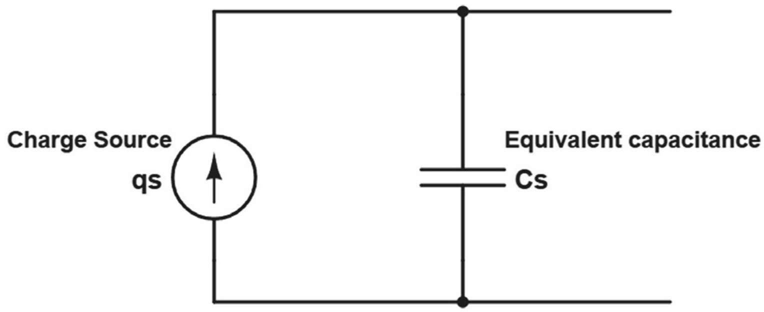

Fig. 6 Piezoelectric sensor

Some of the applications of capacitive sensors are motion sensing [20], gauging and metrology [21], object detection [22], liquid level sensing [23], material testing, environmental sensing [24], flow sensing [25–30], and biomedical applications [31–34].

2.1.6 Piezoelectric Sensors

A piezoelectric accelerometer is a device that detects and quantifies changes in mechanical variables such as vibration, acceleration, and mechanical shock. It achieves this by harnessing the piezoelectric effect of specific materials. The piezoelectric effects can be classified into four distinct categories: the longitudinal effect, shear effect, transverse effect, and hydrostatic effect. However, the fabrication of CNF films is characterized by their physical, dielectric, and electromechanical behavior. Industry compares the nonlinearity and hysteresis of piezoelectric sensors with those of polyvinylidene fluoride (PVDF), a reference piezoelectric polymer [35, 36]. Figure 6 presents a piezoelectric sensor, where qs represents the source's charge and Cs stands for capacitance.

Piezoelectric actuators framework a significant portion of the transducer market, with applications in automotive systems, active vibration damping, medical imaging, precision positioning, industrial machinery, and consumer electronics [36].

2.1.7 Accelerometer

An accelerometer measures an object's or body's acceleration in its immediate reference frame. An accelerometer doesn't measure acceleration in terms of coordinates. Accelerometer sensors have diverse applications in various electronic products, including smartphones and wearable gadgets. A micro-machined piezoelectric sensing element combines with a miniature wireless accelerometer to measure mechanical vibrations [37].

2.1.8 Strain Gauge

With the growing utilization of strain gauges, the techniques and principles controlling the behavior of composite materials are being adjusted accordingly. The application of a strain gauge to an isotropic material [38] results in the manifestation of a thermal output, commonly referred to as apparent thermal strain. Transverse sensitivity denotes to the unfavorable consequence of being sensitive to strains that are perpendicular to the direction of the grid. The user typically measures it as a percentage and determines its magnitude by dividing the sensitivity in the direction perpendicular to the grid axis by the sensitivity in the grid axis' direction. The foil strain gauges exhibit a transverse sensitivity that ranges from a few percent. Self-temperature compensated (S-T-C) strain gauges have zero thermal output on tested materials, causing thermal compensation loss. Even with a correctly chosen strain gauge, orthotropic behavior and transverse sensitivity combine to leave behind thermal output. Materials like composite behave orthotopically, which also produce the different transverse sensitivity effects [39, 40].

2.1.9 Torque Sensor

The unique wrist force or torque sensors used by the industries have four degrees of freedom (DOF) for haptic-based human–computer interface systems. The 4 DOF sensor is more cost-effective than conventional 6 DOF sensors because of its simplified structure and reduced strain gauge demands. Six-axis MEMS force torque sensor is used by industry to measure the torque components on various axes. Two force components and one torque component must be measured, to characterize magnetic material properties. Figure 7 presents a basic torque sensor, with fx, fy, and fz representing generalized forces or moments acting on the torque sensor in the x, y, and z axes, respectively. Torque sensors are commonly used in robotics to control joint movements. Various industries, including automotive, also use torque sensors [41–44].

2.1.10 Gyroscopic Sensors

The gyroscope device attaches a disk to a frame and detects angular velocity when the frame rotates. There are various classes of gyroscopes that depend on the physical and technological aspects of their operation. A gyroscope can work by itself or as part of a more complicated system, such as an Inertial Measurement Unit (IMU), gyrocompass, attitude heading reference device, or method for navigation. A gyroscope's operational mechanisms include rotational movement along specific axes. The gyroscope uses capacitance variations to detect the displacements of the object.

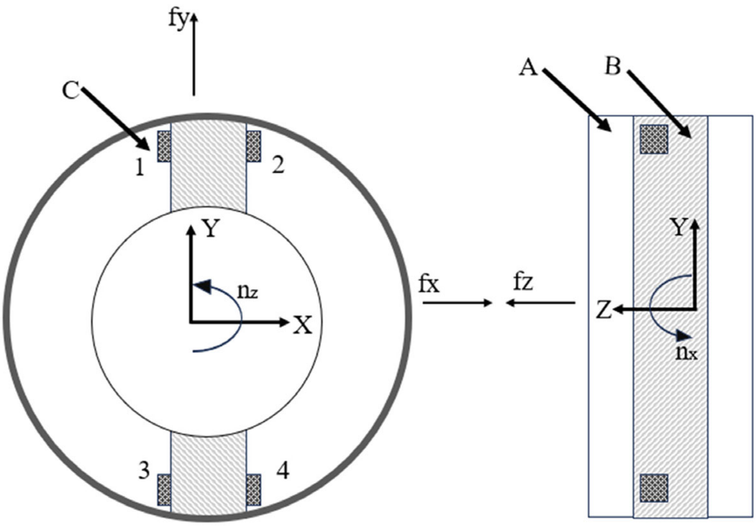

Fig. 7 Basic torque sensor structure **a** solid disks, **b** elastic element, and **c** strain gauge

2.1.11 Thermo-Fluid Sensors

There are different types of sensors that involve fluid flow, thermodynamics, heat transfer, and pressure sensors.

Fluid Flow: Sensors to detect variables such as pressure, velocity, and flow rate are used in fluid flow applications, which provide valuable information for efficient system operation, anomaly identification, and performance improvement [45]. These sensors ensure system efficiency, identify anomalies, and enhance overall system performance.

Thermodynamics: Sensors are used to measure temperature, pressure, and other factors to monitor and control industrial operations, refrigeration units, and heating and cooling systems [46].

Heat transfer: Heat-transfer-detecting sensors are essential in applications like HVAC systems, which monitor temperature differentials to maintain a suitable indoor environment [47]. Additionally, renewable energy fields like solar power plants use sensors to monitor and optimize the power output.

Pressure: It is essential to comprehend and analyze the pressure exerted on the wings of insect-like flying robots in order to quantify their pressure accurately. Utilize a pressure sensor with a weight that is at least one-tenth of the weight of the wings [48].

Thermo-fluid sensors are utilized in various sectors and situations where it is crucial to monitor and manage temperature and fluid flow [49].

2.1.12 MEMS Respiratory Flow Sensor

MEMS respiratory flow sensors play a crucial role in modern respiratory care because they provide accurate and real-time measurements. A sensor information feedback system uses a high-speed MEMS flow sensor to self-adjust the solenoid valve's open time to accurately dispense desired volumes of reagent. A high-speed liquid flow sensor detects the pressure differential across a flow channel for both static and dynamic liquid dispensing. A closed-loop control system assesses the valve open time for any fluctuations in liquid viscosity and pressure in each dispensing cycle. Techniques for monitoring respiratory flow include the measurement of transthoracic impedance, blood oxygen and carbon dioxide concentration, and direct measurement of breathing airflow. The relationship between flow rate and measured voltage in resistive breathing airflow measurements is linear. The cost of instrumentation can be significantly decreased with a MEMS respiratory flow sensor. A piezoelectric cantilever deform occurs when the exhaled breath flow velocity applies pressure to the sensor surface [50].

2.1.13 Thermocouple

When a variation in temperature causes an electrical potential difference that arises between two different metallic materials, thermocouples function by harnessing the Seebeck effect at that time. The voltage is directly proportional to the temperature difference between the measuring junction and the reference junction. Many industries use these materials due to their high-temperature resistance, durability, and suitability for high-temperature environments [51, 52], including manufacturing, automotive, and aerospace [53, 54]. Figure 8 shows a thermocouple.

2.1.14 Thermistor

A thermistor is a type of resistor that acts as a thermometer by changing its resistance based on temperature. Thermistor sensors provide a change of resistance, and the typical power range is 1 μW to 10 mW [55]. In reaction to variations in heat transfer, which for a given geometry is mostly a function of the air speed and temperature, thermistors can offer velocity data. Thermistors have more stability, resilience, and accuracy at low velocities than conventional thermal anemometers like hot wires [56]. The creation of thermos-resistors typically involves the use of semiconductor materials suitable for their temperature-dependent resistance change. These materials are typically doped ceramics or a mixture of several metal oxides, including cobalt, copper, magnesium, manganese, titanium, and nickel [57]. The temperature coefficient of resistance (NTC) of thermocouples is typically negative. A substance with a high degree of temperature sensitivity makes up a thermistor. The material that comprises a thermistor has a high degree of temperature sensitivity. The material's resistance is directly correlated with its temperature-calibrated expansion and

Fig. 8 Thermocouple

contraction. Figure 9 presents a schematic diagram of a thermistor. In this figure, the brightness of the light bulb varies with the measured temperature [58].

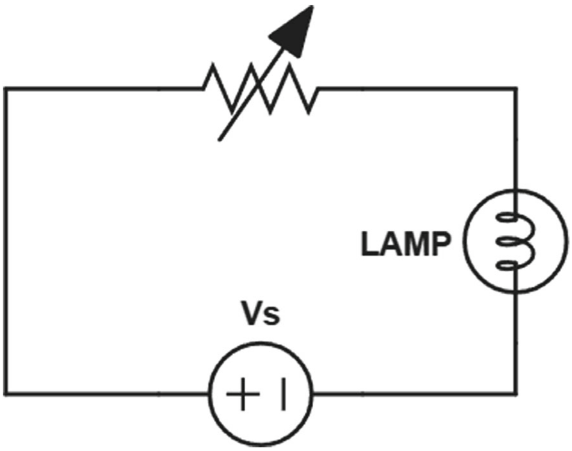

Fig. 9 Schematic diagram of thermistor

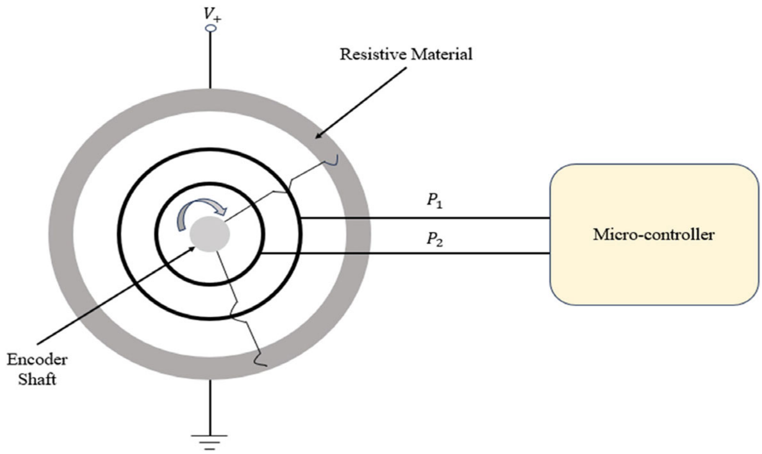

Fig. 10 Shaft encoder

2.2 Digital Sensors

Industries use different types of analog sensors for different mechatronics systems. This part of the book highlights the working principles and applications of analog sensors.

2.2.1 Shaft Encoder

An encoded disk which is a resistive material and a decoding device combine to form an absolute shaft encoder, also known as a rotary encoder. The encoded disk or the resistive material contains positional information obtained using linear codes or mechanical patterns. While the disk rotates with the object, a decoding unit interprets these codes or patterns and converts the location information into analog or digital signals by a microcontroller. Industrial equipment, such as machine tools, automobiles, robotic arm control, aircraft, radars, antennas, and conveyor systems, widely uses shaft encoders to measure and control the angular position of rotating objects [17, 59]. Figure 10 shows the shaft encoder.

2.2.2 Motion Sensing by Encoder

An encoder is a sensor that gives the feedback of the system. Encoders convert motion into an electrical signal, which is a control device in a motion control system by using light emitters and light detectors, like a counter or PLC, and can interpret. The encoder transmits a return signal to determine the position, count, speed, or

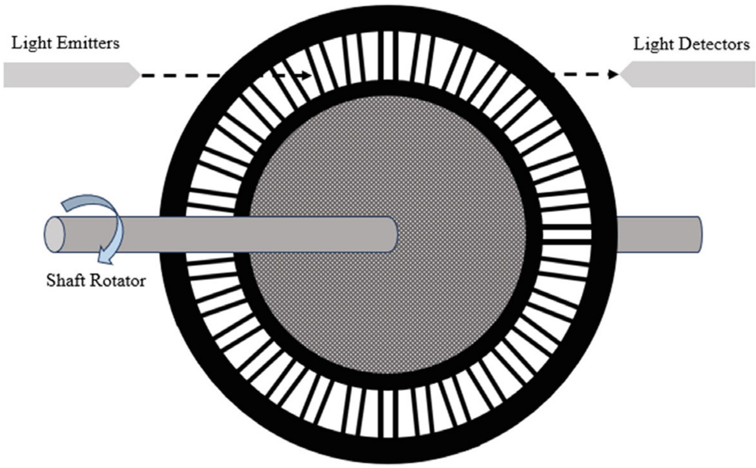

Fig. 11 Motion sensing by encoder

direction. Elevators, pointing mechanisms, and servomotors use this encoder [60, 61]. Figure 11 shows motion sensing by encoder.

2.2.3 Laser Doppler Interferometer

Laser Doppler Velocimetry (LDV) is a method that enables the precise measurement of velocity at a specific location within a flow field, with a focus on capturing rapid changes over time. To examine the material properties, calibrate sensors, and measure force in dynamic circumstances, the laser Doppler interferometer (LDI) can be utilized. It has a wide range of applications in various fields such as Flow Research, Automation, Medical Applications, Navigation, Calibration and Measurement Spectroscopy, Metrology, Gravitational Wave Detection, NVH Optimization (Noise, Vibration, Harshness), Measurement of Material Velocity, etc. [62–64]. Figure 12 shows Laser Doppler Interferometer.

2.2.4 Light Sensors

A light sensor generates an output signal that represents the brightness of light by measuring the radiant energy within a particular frequency range known as the "light" spectrum. This spectrum includes all of the frequencies from "infrared" to "visible" and even "ultraviolet" light. Figure 13 shows four types of light sensors that include photoresistor, photodiode, phototransistor, and photo-FET. Light sensors are used in consumer electronics, streetlights, automobiles, security systems, photography, solar panels, display backlight control, proximity sensors, agricultural monitoring systems, photoelectric rangefinders, and memory material illumination sensors [65].

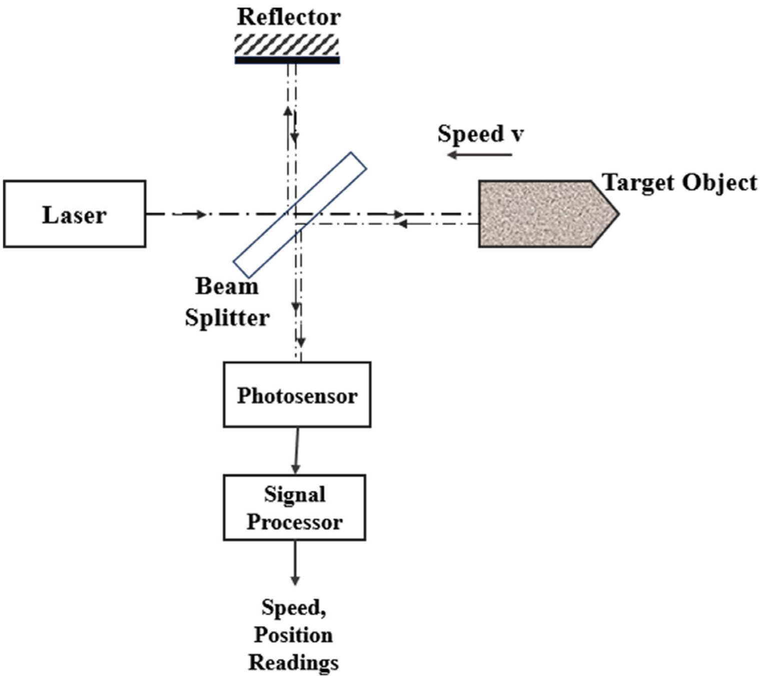

Fig. 12 Laser doppler interferometer

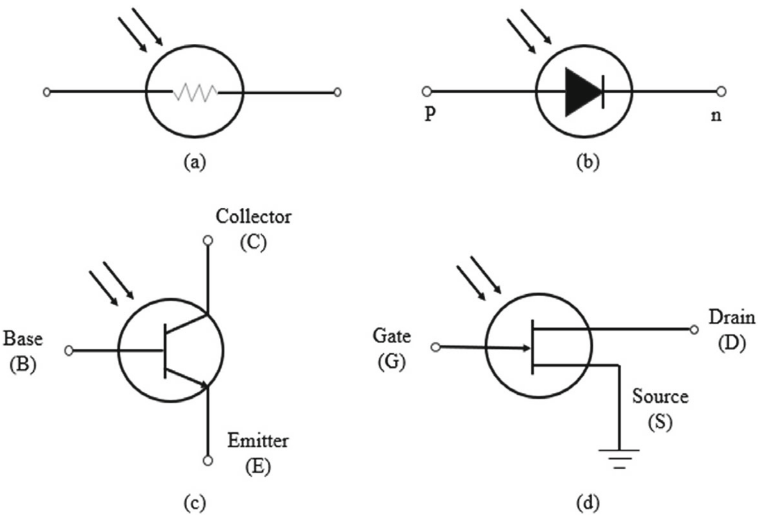

Fig. 13 Four types of light sensors

Photoresistor: At high light on their sensitive surfaces, photoresistors, which are passive electronic parts, lose resistance. They are also known as photocells, light-dependent resistors (LDRs), or photo-conductive cells. This phenomenon is known as photoconductivity. Researchers are using silica nanopillars as a substrate for cadmium sulfide (CdS) in photoresistors for the first time. The substrate with nanopillars, which has a high surface ratio, can enhance the amount of sensitive material and the light-responsive surface area. Consequently, this significantly enhances the photosensitivity of the CdS photoresistor [66]. Photoresistor sensors find use in various fields such as light measurement and detection systems, medical practice, optical communication, security monitoring, analytical instrumentation, industrial control, and home automation [67, 68].

Photoresistor: A photodiode is a type of semiconductor diode that can detect and respond to several forms of photon radiation, including visible light, infrared or ultraviolet radiation, X-rays, and gamma rays [69]. A photodiode resistor is also useful in weather forecasting applications because it can measure solar irradiation [70, 71]. Systems for light measurement and detection, environmental and security monitoring, analytical instrumentation, industrial control, home automation, and modern agriculture also utilize it.

Phototransistor: A phototransistor is a device that converts incoming photons into electrons at the base of a bipolar transistor. The flow of current from the base causes a larger current to flow between the collector and emitter just like the other transistor. A circuit then detects the increase in current. Electronic devices and industrial automation systems use phototransistors as ambient light sensors to detect objects, measure distances, and control processes based on light signals [72].

Photo-FET: A photo-FET, or photo-field-effect transistor, is a specialized semiconductor device that modulates its conductivity in response to light. It works by adjusting the conductivity of the semiconductor channel in response to light, where photodiodes and phototransistors both use the photoelectric effect. The gate-source voltage is adjusted to create this modulation [73]. Photo-FETs can be used in optical communications and high-speed light sensing applications.

2.2.5 Hall Effect Sensor

A Hall effect sensor, also known as a Hall sensor or Hall probe, incorporates one or more Hall elements. These elements utilize the Hall effect, named after scientist Edwin Hall, to generate a voltage that is directly proportional to a specific component of the magnetic field vector B. A low voltage output, usually in the range of a few microvolts per gauss, is generated by the Hall Effect magnetic sensors. As a result, these sensors often come with built-in high-gain amplifiers [74]. There are two classifications of Hall Effect sensors: one that produces analog output and another that generates digital output. The analog sensor comprises a voltage regulator, a Hall element, and an amplifier. An analysis of the circuit diagrams reveals that the

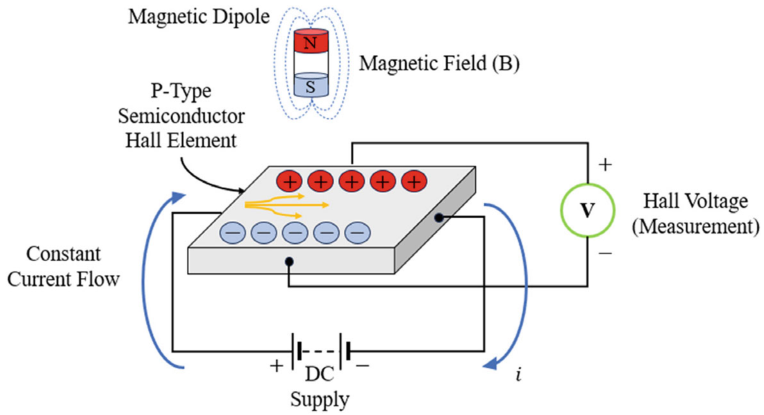

Fig. 14 Hall effect sensor

sensor's output is analog and has a direct correlation with either the Hall Element output or the intensity of the magnetic field. These sensors are suitable and used for monitoring proximity because of their consistent linear output. The Hall effect sensors have advantageous characteristics like thermal stability and high sensitivity. Moreover, they have very low detection limits. Because of their uniqueness, planar Hall effect sensors are used in nano-Tesla (nT) magnetometers, current sensing, or low magnetic moment detection in lab-on-a-chip devices [75, 76]. Figure 14 shows Hall effect sensor.

2.2.6 Ultrasonic Sensors

An ultrasonic sensor measures the distance between itself and an object by using ultrasonic sound waves that use a transducer to produce and detect ultrasonic pulses that identify how far away the object is. Sound waves are produced and emitted by a transmitter using piezoelectric crystals, and a receiver captures any reflections of these waves. The sensor captures and transforms the sound that bounces off the intended object into digital or electronic signals for later analysis or manipulation. Assessing surface characteristics, identifying object position, and computing object velocity, ultrasonic sensors have found extensive applications in such tasks. Also, in-vehicle detection uses an ultrasonic sensor [77]. The observer can use the ultrasonic sensors to determine the position and velocity of moving objects like cars, buses, etc. The vehicle passes the ultrasonic sensor at the roadside [78]. Some applications of ultrasonic sensors are industrial sensing, precision actuation, material processing and manufacturing, medical imaging, and medical therapy [79–81]. Figure 15 shows the ultrasonic sensor.

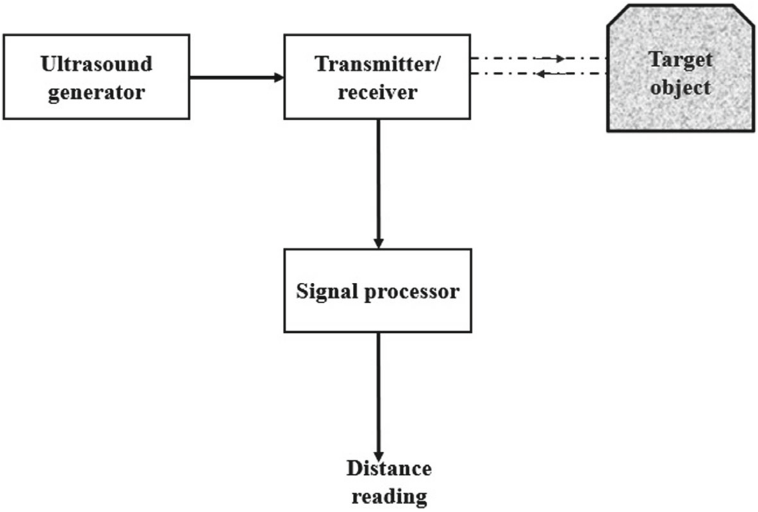

Fig. 15 Schematic diagram of ultrasonic sensors

2.2.7 MEMS Sensors

MEMS sensors are compact devices utilized for the measurement of physical parameters such as pressure, temperature, acceleration, and magnetic fields. Advantages like compactness, light weightiness, superior performance, convenient mass production, and affordability are offered by MEMS technology [82]. Depositing thin material layers onto a silicon substrate and then selectively removing areas to create 3D formations like diaphragms, beams, levers, springs, and gears are involved in MEMS IC manufacturing. Tilting the sensor causes a change in electric potential, quantified as capacitance. The industry can modify the aforementioned signal to generate a consistent output signal in either digital, 4–20 mA, or VDC format.

There are four types of MEMS sensors:

- MEMS accelerometer.
- MEMS gyroscopes.
- MEMS pressure sensors.
- MEMS magnetic field sensors.

Using a MEMS capacitive force sensor, researchers investigated the mechanical properties of soft hydrogel microcapsules as a protein delivery mechanism. Many industries like petrochemical, industrial, and construction services sectors, power generation, aerospace, defense, and healthcare currently utilize MEMS. They are also essential parts of computers, phones, digital cameras, game consoles, and automobiles, and they play a significant role in daily life [83, 84]. Figure 16 shows MEMS sensor.

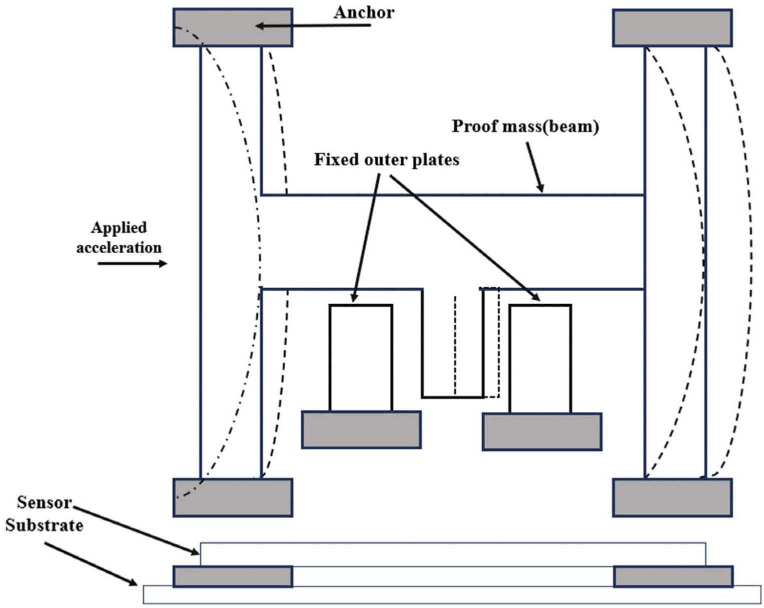

Fig. 16 MEMS sensors

2.3 Sensor Fusion

Sensor fusion is the combination of sensor data or data generated from other sources in order to generate information with reduced uncertainty compared to using these sources individually. Different types of techniques, such as the extended Kalman filter, combine data from the Global Positioning System (GPS) and the inertial navigation system (INS). This is particularly useful, for example, in determining the orientation of an airplane with inexpensive sensors. This is one of the uses of sensor fusion [85]. Railway systems also incorporate sensor fusion [86]. Automation, automotive driver assistance systems, autonomous robots, C3I, etc. are some other applications of sensor fusion [87].

3 Actuator

An actuator is a machine component that, when provided with an electrical, pneumatic, or hydraulic input in a system (referred to as an actuating system), creates force, torque, or displacement, usually in a controlled manner. An actuator transforms such an input signal into the necessary kind of mechanical energy [88].

3.1 Stepper Motors

A stepper motor is an electric motor that rotates in a sequence of small angular steps rather than continuously. It is also known as stepping motor. The stepper motor is an electromechanical device that transforms electrical energy into mechanical energy. It consists of a permanent-magnet rotor and an electromagnet stator and it follows the principle of electromagnetism. It can generate a magnetic field by supplying power to the stator coil that in turn causes the rotor to rotate in response to the rotating magnetic field. This motor operates on a fundamental functioning principle. Stepper motors play a crucial role in the field of robotics. Robotic applications necessitate accurate and exact motions. The stepper motor drive specifically builds and rigorously tests its software and hardware circuits to accommodate various types of stepper motor movements [89, 90].

3.2 DC Motor

A direct current motor or DC motor is an electrical device that uses a direct current to create a magnetic field in order to convert electrical energy into mechanical energy. The stator of a motor is usually placed outside and the rotor is outside.

The stator contains electromagnetic windings or permanent magnets, while the rotor's coil windings are powered by DC current. Rotor magnets are attracted to and repelled by the magnetic field produced in the stator by DC current. After that rotor spins and motor employ commutators to turn the rotor. The rotor stops spinning when it aligns with the magnetic field, but the magnetic field is reversed since the commutator reverses the stator current. This keeps the rotor rotating. The right image shows a schematic of the DC motor. A study goes into great detail about a five-phase brushless DC (BLDC) motor that was made for an electro hydrostatic actuation system (EHA) that works well with thin, well-designed wings [91]. Figure 17 shows a DC motor. The main applications of DC motors include the manufacture of pulp, paper, and paperboard; the propulsion of electric vehicles; textile industries; and public transportation like subway and trolley systems [92, 93].

3.3 Synchronous Motor

A synchronous electric motor precisely synchronizes its shaft's rotation with the frequency of the provided electrical current in a stable condition. Due to their ability to maintain speed, coordinate with the grid, and support reactive power, synchronous generators are widely used in Power Plants for electricity generation. The time it takes for one complete shaft rotation is equivalent to a full number of AC cycles [94]. High-performance driving applications such as industrial robots and machine

Fig. 17 DC motor

tools frequently utilize synchronous motors due to their high power density, high torque-to-inertia ratio, and low maintenance requirements [95, 96].

3.4 Hydraulic Pumps and Motors

A hydraulic pump is a mechanical device that converts mechanical power into hydraulic energy. In the form of flow and pressure, it specifically converts the hydrostatic energy. Agricultural equipment uses hydraulic pumps and motors to enhance its efficiency. The most significant application of hydraulic pumps and motors is to improve the overall efficiency of agricultural equipment, such as tractors, harvesters, planters, fertilizers, sprayers, and attachments [97, 98]. Figure 18 shows hydraulic pump.

3.5 Hydraulic Valves

A hydraulic valve is a mechanical device that controls the movement of hydraulic fluid inside a hydraulic system. Their high-pressure hydraulic systems are commonly characterized as ranging from 200 bar to an average of 700 bar or higher. The system uses the hydraulic valves to regulate the fluid's flow rate. The system also monitors and controls the fluid pressure and direction. Electro-hydraulic control valves are critical hydraulic components used in industrial and aerospace applications to regulate electro-hydraulic motion. Electro-hydraulic control valves are becoming increasingly digital, integrated, and intelligent to meet the demands of Industry 4.0, due to

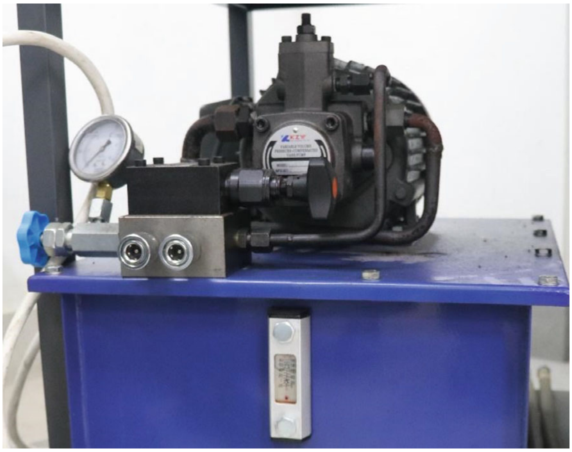

Fig. 18 Hydraulic pump

the advancements in automation, digital technology, and communication technology [99].

4 Sensor and Actuator Integration in Mechatronic System

The integration of sensors and actuators into mechatronic systems requires a series of crucial stages.

4.1 Signal Acquisition and Conditioning

Sensors perceive physical characteristics and help transform them into electrical impulses. These signals frequently require conditioning, such as amplification or filtering, in order to be functional. Signal conditioning includes tasks like boosting weak signals, getting rid of noise, and adjusting signals to a range that works with the analog-to-digital converter (ADC) if the system uses digital processing [100].

4.2 Signal Processing

Microcontrollers and microprocessors handle the processed signals received from sensors. They implement control algorithms to ascertain the suitable reaction. Control algorithms can range from basic, such as proportional control, to more intricate ones like PID control and model predictive control [101].

4.3 Actuation Control

The processor generates signals and transmits them to actuators in order to produce the intended physical reaction. Power electronics, such as H-bridges for motor control and valve drivers for hydraulic actuators, regulate power flow to actuators according to control signals [102].

4.4 Feedback and Closed-Loop Control

For achieving an accurate control, Feedback loops are crucial in mechatronics system. The user compares the required values by constantly monitoring the sensor data. Error correction involves the manipulation of actuator signals to minimize the discrepancy between the measured and desired states. The integration process utilizes both wired and wireless communication protocols [103]. Common wired communication protocols for exchanging data between sensors, actuators, and controllers include I2C, SPI, UART, TFT, and CAN buses. When establishing physical connections is not feasible, wireless communication applications use Bluetooth, Zigbee, and Wi-Fi [104]. Software integration employs embedded software such as real-time operating systems or firmware to handle tasks such as sensor data collection, processing, and control logic implementation, while MATLAB/Simulink facilitates the simulation and modeling of control methods [105]. Here is an illustration of a system that integrates both a sensor and an actuator. An ADC process detected the finger presence from a capacitive touch sensor and servo motor into a digital signal. A microprocessor determines if the touch threshold has been surpassed or not by interpreting the digital signal by enhancing the device's functionality [106]. To adjust the position of a servo motor [107], the microcontroller uses a control algorithm and regulates its movement through PWM signals. The motor installs a position sensor for precise control, enabling closed-loop control via feedback from the microcontroller. This ensures precise and efficient motor operation.

5 Conclusion

The integration of sensors and actuators in designing a mechatronics system is essential for the advancement of many industries, including robotics, automation, and manufacturing. This integration enhances the system's functionality and performance. Moreover, mechatronics' multidisciplinary character offers a wide choice of options for completing particular functionality. To attaining optimal system performance in mechatronics system, integrating sensors and actuators is essential. Sensors can sense unknown characteristics of a mechatronics or engineering system and its surroundings. They are able to monitor the system and collect data about it. This will support system operation and control. Actuators, such as stepper motors and hydraulic pumps, are necessary for plants to function. Control actuators are required for various control equipment to operate. Furthermore, mechatronics, as an integrated technology, advances due to the ongoing development of microelectronics and other technologies. In today's engineering curriculum, mechatronic system design and comprehension are becoming more and more crucial to stay up with the rapidly changing technological landscape.

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