ALIGN GUARD INTERNS

Report On

IMU, ACCELEROMETER, EMG Sensors

Submitted by

Blessy Louis
Christ University
Blessylouis2002@gmail.com

MAY 2024

TABLE OF CONTENTS

ABSTRACT

This report provides an in-depth analysis of the working principles, interfacing techniques, calibration procedures, and data characteristics of Inertial Measurement Units (IMUs), accelerometers, and Electromyography (EMG) sensors. IMUs integrate accelerometers, gyroscopes, and magnetometers to measure an object's specific force, angular rate, and orientation, using communication protocols like I2C, SPI, and UART for interfacing. Calibration involves bias correction, scale factor adjustment, and alignment to ensure accuracy. Accelerometers, which measure linear acceleration through voltage changes in microscopic crystals, also rely on similar interfacing methods and require static and dynamic calibration. Their data is characterized by sensitivity, range, and noise. EMG sensors detect electrical activity in muscles using electrodes, amplifiers, and filters, with calibration focusing on proper electrode placement and skin preparation to minimize noise. EMG data is characterized by amplitude, frequency, and signal-to-noise ratio. This comprehensive examination highlights the critical aspects of these sensors, emphasizing the importance of precise calibration and interfacing for accurate data collection in applications spanning robotics, mobile technology, and biomedical fields.

CHAPTER – 1

INERTIAL MEASUREMENT UNIT (IMU)

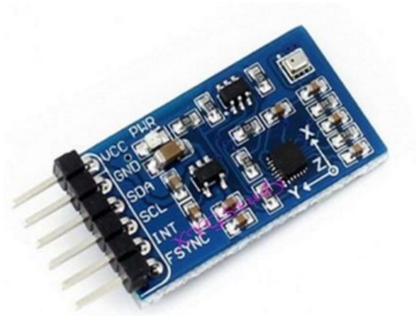

Figure-1: IMU Sensor

A complex tool used to track and measure an object's direction, velocity, and gravitational forces is called an Inertial Measurement Unit (IMU). IMUs are the quiet navigators that power a variety of operations, including space launches, the minuscule motions of your smartphone when navigating urban streets, and even piloting drones across the skies.

An Inertial Measurement Unit (IMU), often referred to as a Motion Reference Unit (MRU) or Inertial Reference Unit (IRU), is a 6-axis IMU that combines a 3-axis gyroscope and a 3-axis accelerometer. Some of them become 9-axis IMUs by adding a 3-axis magnetometer. When combined, these sensors provide a complete image of the device's motion by measuring the particular force, angular rate, and magnetic fields around it. IMUs are essential for controlling a variety of vehicles, including missiles, motorbikes, and airplanes. They are essential to heading and attitude reference systems, which help these vehicles navigate and control precisely. IMUs are also essential to spacecraft, helping landers, satellites, and unmanned aerial vehicles (UAVs) navigate in space. Additionally, IMUs improve GPS dependability in difficult situations by guaranteeing precise navigation in locations with electronic interference or tunnels. An Inertial Measurement Unit measures rotational rate using a gyroscope, detects linear acceleration using accelerometers, and, in some situations, uses a magnetometer as a heading reference.

CHAPTER – 2

COMPONENTS AND WORKING

One accelerometer, gyroscope, and magnetometer are usually included in each of the three major axes (pitch, roll, and yaw) to provide full information on the object's motion and orientation in three-dimensional space.

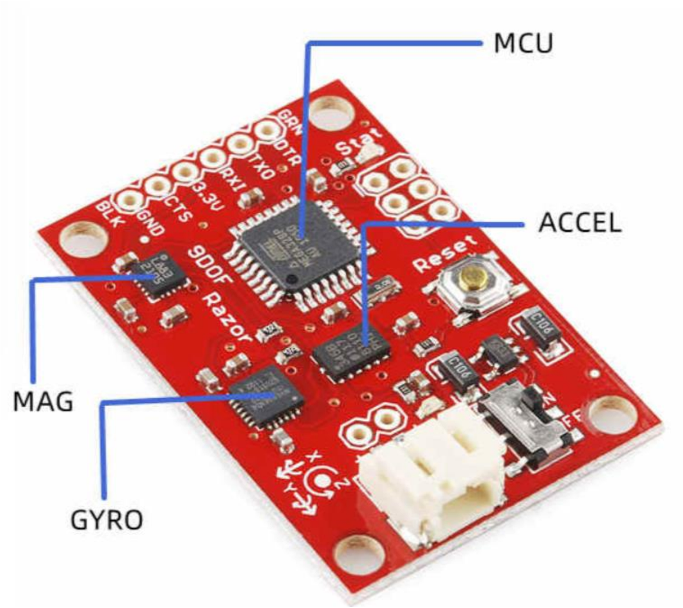

Figure-2: Pictorial representation of the components of IMU

2.1 ACCELEROMETER

There are several different types of accelerometers, such as mechanical, quartz, and MEMS accelerometers. Accelerometers are clever devices that measure and convey certain forces. In spite of their size and expense, mechanical accelerometers are mostly utilized in navigation-grade applications, even though they can reach in-run bias stabilities of less than 1 µg.
In-run bias stability is provided by quartz and MEMS accelerometers, encompassing a range of performance categories from 1000 µg to 1 µg. They work with great precision and stability in fields including aerospace, military, automobile testing, and geophysical exploration, where precise acceleration measurement is crucial. Microelectromechanical systems, or MEMS technology, is frequently used by the accelerometers in IMUs. These accelerometers use a little mass that is spring-connected to a reference system. The accelerometer then uses electrical means to detect this shift, corrects it for accuracy, and analyses the information to determine the amount of acceleration.

The mass travels in proportion to the applied acceleration during the entire operation, which is governed by Hooke's law and Newton's second law. Put simply, it functions something like a small sensor that detects when anything is accelerating or decelerating.

2.2 GYROSCOPES

An IMU's gyroscopes calculate angular velocity, which shows how quickly and which way something is turning. Modern gyroscopes come in a variety of forms, such as quartz/MEMS gyroscopes, ring laser gyroscopes (RLGs), mechanical gyroscopes, and fibre-optic gyroscopes (FOGs). Consumer, industrial, and tactical industries use quartz and MEMS gyroscopes, but fibre-optic gyroscopes are used in all performance categories. Ring laser gyroscopes are appropriate for tactical and navigation grades because of their in-run bias stabilities, which range from 1 °/hour to less than 0.001 °/hour. The best performing gyroscopes are mechanical ones, which may have in-run bias stabilities of less than 0.0001 °/hour. The Coriolis effect, which describes forces when an item moves in a rotating frame of reference, is the basis for MEMS gyroscopes, which are widely employed. A circular platform spinning in a clockwise direction serves as an example of the Coriolis effect in MEMS gyroscopes. A vibrating proof mass that is fixed to a reference frame in a standard Coriolis MEMS gyroscope causes a secondary vibration that is perpendicular to the driving axis as it rotates. A signal proportionate to the Coriolis force and the detected rotation is obtained from this secondary vibration, which is detected by capacitance variations.

2.3 MAGNETOMETERS

An instrument that monitors the magnetic field's intensity and direction is called a magnetometer. Compasses, which show the direction of the Earth's magnetic field, are a common example. Certain magnetometers detect magnetic dipole moments, which are related to pairs of poles or closed electric current loops.

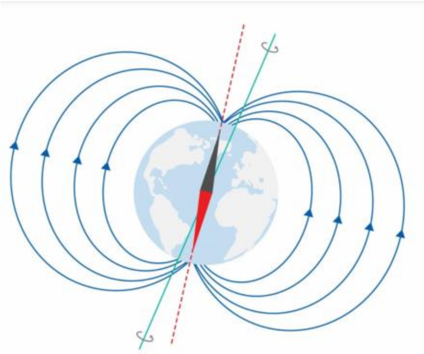

Figure-3: Magnetic dipole moments

Different types of magnetometers function by aligning with magnetic fields or by using magnetoresistance, magneto induction, or the Hall effect to cancel forces.

A voltage differential, or Hall voltage, is produced across a conductor by the Hall effect when it is subjected to an applied magnetic field that is perpendicular to the current flow. By using semiconducting materials and flowing current through them to detect variations in current caused by neighbouring magnetic fields, magnetometers are made possible by this approach. The magnitude of the magnetic field is directly proportional to the resultant Hall voltage.

The magnetization of a substance in response to an external magnetic field is measured via magneto induction. This entails drawing demagnetization curves, sometimes referred to as hysteresis or B-H curves. These charts quantify the force and magnetic flux that a material experiences under various magnetic field conditions. These curves are used by scientists and engineers to categorize materials according to their magnetic characteristics and reactions to external magnetic fields.

Magnetometers detect an object's electrical resistance in reaction to an external magnetic field using this method. Specifically, they use the anisotropic magneto-resistance (AMR) of ferromagnets. When a material is subjected to a magnetic field, its electron orbitals self-distribute, affecting electrical resistance. The resistance is highest when the current aligns with the external magnetic field.

An IMU's capabilities and the kind of data it can give can be greatly impacted by the presence or absence of a magnetometer.

When we discuss an IMU without a magnetometer, we are effectively talking about a sensor system that uses gyroscopes and accelerometers alone to determine the motion of an object.

The IMU performs quite well in this arrangement, offering basic information on angular velocity and linear acceleration. With the gyroscopes monitoring angular rate and the accelerometers recording linear acceleration, its main purpose is to interpret simple orientation changes. But there are drawbacks to not having a magnetometer, especially when it comes to heading accuracy. Accurate heading becomes difficult if one is unable to detect the Earth's magnetic field directly. Because of its intrinsic gyroscopic inaccuracies, the system may experience drift over time, which makes it less suitable for applications needing extremely precise directional information.

On the other hand, an IMU with a magnetometer adds a new level of functionality and greatly improves the system's capacity to deliver precise heading data. By measuring the Earth's magnetic field, the magnetometer enables the IMU to provide better stability when identifying orientation changes and to account for gyroscopic drift. The addition of a magnetometer improves heading accuracy, but it also raises calibration-related issues. In order to correct for static magnetic interference that might cause heading inaccuracies, IMUs with magnetometers usually need to be calibrated either in-situ or while the vehicle is moving. If accurate magnetometer heading is needed, then magnetometer calibration becomes an essential step after installation. Notwithstanding certain difficulties, the benefits in accuracy—particularly in situations requiring accurate heading information—make an IMU with a magnetometer a good fit for augmented reality, robotics, and navigation systems.

CHAPTER – 3

TYPES OF IMUs

IMUs come in a variety of forms, each with its own benefits and appropriate uses. Examples of these include Silicon MEMS IMUs, Fiber Optic Gyro (FOG) IMUs, Ring Laser Gyro (RLG) IMUs, and Quartz MEMS IMUs.

3.1 Silicon MEMS (Micro-Electro-Mechanical Systems) IMUs

Miniaturized sensors that measure mass deflection or the force needed to maintain a mass in place are at the heart of silicon MEMS IMUs. While their noise, vibration sensitivity, and instability characteristics are generally higher than those of FOG IMUs, continuous technical improvements are gradually improving their accuracy. Silicon MEMS IMUs are widely used in consumer electronics because to their small size, lower weight, and affordability. They are commonly used in gaming consoles, smartphones, and tablets for motion detection and gesture recognition. Additionally, they play a critical role in automotive applications, including advanced driver assistance systems (ADAS), navigation systems, and vehicle stability control and rollover detection. Silicon MEMS IMUs are critical to the accurate movement and positioning of robotic systems.

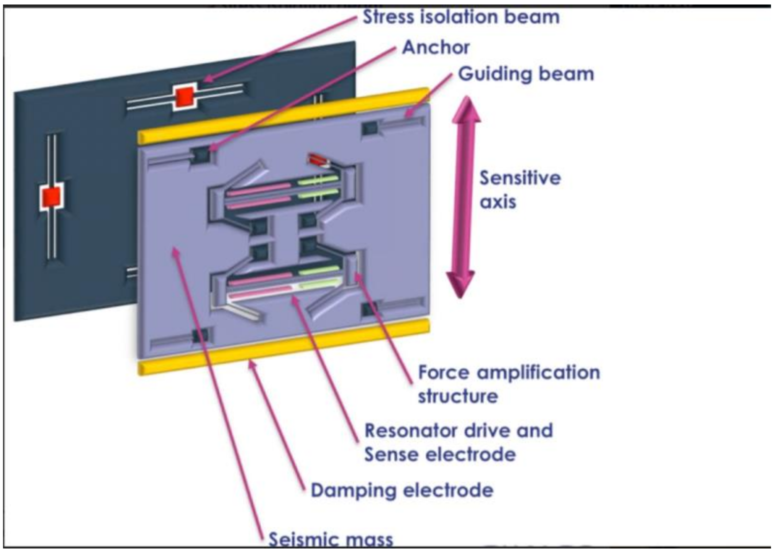

Figure – 4: Silicon MEMS

3.2 Quartz MEMS IMUs

Quartz MEMS IMUs are equipped with a single quartz inertial sensor element that is accurately controlled to vibrate by an oscillator. The angular rate is sensed by this vibrating quartz, which then generates a signal that may be transformed into a DC signal proportionate to the rate. Tactical-grade quartz MEMS IMUs are known for their great temperature stability and dependability, making them competitive with FOG and RLG technologies in SWaP-C (size, weight, power, and cost) parameters. Industrial automation has become a stronghold for these IMUs, especially in robotic arms and automation systems that need exact control and placement. Unmanned aerial vehicles (UAVs) rely on Quartz MEMS IMUs to provide crucial data for control, navigation, and stabilization during flight operations.

3.3 FOG (Fiber Optic Gyro) IMUs

Using a solid-state technique, light beams pass via a coiled optical fiber in FOG IMUs. Their outstanding thermal stability, reduced sensitivity to shock and vibration, and great performance in important parameters make them ideal for mission-critical UAV applications requiring very accurate navigation. FOG IMUs have established a niche in the aviation and aerospace industries despite being more expensive and bigger than their MEMS-based competitors.They are essential for accurate orientation maintenance in space exploration missions as well as navigation, attitude control, and stabilization in aircraft. FOG IMUs are also used in the defense industry, where they are used for targeting and navigation in military vehicles, aircraft, and missiles.

3.4 RLG (Ring Laser Gyro) IMUs

Similar to FOG IMUs, RLG IMUs function by substituting a sealed ring chamber for the coiled optical fiber. RLG IMUs are the most precise choice available, but they are also the most expensive and usually bigger than other technologies. High performance navigation systems are a suitable use for RLG IMUs. They offer exact control over direction during maneuvers and are widely utilized in ships and airplanes. RLG IMUs are essential parts of tanks, armored vehicles, and precision-guided missiles in military applications because they help with precise targeting and missile guidance.

CHAPTER – 4

MERITS AND DEMERITS OF IMUs

4.1 MERITS

Inertial Measurement Units (IMUs) have become integral in various applications, thanks to their numerous advantages. Their compact and lightweight design is a significant feature, enabling their integration into technologies where space and weight constraints are critical. This makes them especially suitable for drones, robots, and wearable devices, where maintaining a sleek and functional form factor is essential. The portability and unobtrusiveness of IMUs ensure they can be embedded into devices without compromising their overall design and functionality. One of the standout benefits of IMUs is their versatility in different environments. Unlike navigation systems that depend on GPS signals, IMUs can operate seamlessly in environments where GPS signals are weak or unavailable, such as tunnels, urban canyons, or indoor spaces. This adaptability makes them reliable in scenarios where consistent and uninterrupted navigation data is essential, ensuring performance is maintained regardless of the surroundings.

IMUs also excel in providing continuous measurements, a critical advantage in dynamic applications. They offer real-time data tracking for the movement of objects or individuals, which is invaluable in fields like sports tracking, where athletes' movements need to be monitored with high precision, or in vehicle navigation systems that require instant feedback for accurate positioning and control. The ability to deliver immediate and precise information is paramount in these applications, enhancing performance and safety.

Furthermore, IMUs are cost-effective compared to alternative navigation systems. Their relatively low cost has contributed to their widespread adoption, particularly in consumer electronics, where production costs are a significant consideration. The affordability of IMUs makes them accessible for a wide range of applications, from high-end robotics and aerospace to everyday consumer devices, ensuring that advanced navigation and tracking capabilities can be integrated without prohibitive costs. This economic advantage supports their extensive use across various industries, making advanced sensing technology available to a broader market.

4.2 DEMERITS

Despite their many advantages, Inertial Measurement Units (IMUs) also exhibit certain limitations and drawbacks that need to be considered in their application. One significant challenge is the potential for drift in measurements over time. Drift manifests as a gradual loss of accuracy in determining an object's orientation, velocity, and acceleration, necessitating periodic calibration to ensure that IMUs maintain precision and reliability, especially during extended usage. Additionally, IMUs are susceptible to various forms of noise, which can introduce inaccuracies in their measurements. External factors such as vibrations, electromagnetic interference, and temperature fluctuations can impact data quality. Effectively filtering out this noise requires sophisticated algorithms and signal processing techniques, adding a layer of complexity to their implementation. Furthermore, calibration emerges as a practical requirement for IMUs. This process, while essential for maintaining accurate measurements, can be intricate and time-consuming. The need for specialized equipment and expertise in calibration adds to the overall complexity of integrating IMUs into systems and devices.

CHAPTER – 5

IMU CALIBERATION METHODS AND PROCESS

An instrument used to measure an object's acceleration and angular velocity in three dimensions is called an inertial measurement unit, or IMU. Three gyroscopes and three accelerometers make up the IMU, which measures an object's acceleration and angular velocity along three orthogonal axes. IMUs are extensively employed in a variety of industries, including navigation, robotics, drones, augmented reality, etc., since they can continuously supply attitude and position data. To increase the system's location and navigational accuracy, the IMU must be calibrated accurately. Understanding the IMU's error characteristics through calibration can help us develop algorithms that increase measurement accuracy by making up for the inaccuracy.

Static calibration and dynamic calibration are the two basic categories into which IMU calibration techniques fall. While dynamic calibration is primarily used to assess the IMU's nonlinear error and coupling error, static calibration is mostly used to assess the IMU's zero bias and scale factor error.

Typically, the static calibration method is used in a static condition. The zero bias and scale factor inaccuracy of the IMU are determined by gathering its static data in various orientations. Although this approach is straightforward and simple to use, it is unable to assess the IMU's coupling and nonlinear errors.

5.1 Zero offset calibration

To make sure the IMU is free from outside pressures, place it on a horizontal platform and maintain its position. For a while, record the output data from the accelerometer and gyroscope. It is necessary to capture the output data on each axis independently for three-axis gyroscopes and accelerometers. Determine the average for the accelerometer and gyroscope data for each axis. The zero offset parameter on this axis is this average value. The IMU's output offset in the absence of an external force is reflected by the zero offset parameter.

5.2 Scaling factor calibration

Set the IMU up in a reference system whose angular velocity and acceleration are known. Accurate acceleration and angular velocity data may be obtained from this reference system and compared to the IMU output data. Take note of the IMU and reference system's output data. The acceleration and angular velocity numbers should be included in this data. Determine the scale factor parameters using the IMU's output data and the known angular velocity and acceleration. The proportionate relationship between the real value and the IMU output value is shown in the scale factor parameter.

Dynamic Calibration method

It is necessary to use the dynamic calibrating approach in a dynamic setting. It is possible to assess the IMU's coupling and nonlinear errors by gathering data while it is in motion. Although the operation of this approach is very sophisticated, it can examine the error characteristics of the IMU more thoroughly.

Calibration data processing

Adjustment The calibration process involves a number of processes, the most essential of which include data preparation, parameter estimation, error model development, and others. In order to lessen the influence of noise, the primary steps in data preparation include filtering and smoothing the original data. The selection of an acceptable error model to characterize the error behavior of the IMU is the first step in establishing the error model. Optimization methods are used in parameter estimation to solve the error model's parameters.

Evaluation of calibration results

Comparing the data before and after calibration is the primary method used in the evaluation of calibration outcomes to assess the calibration impact. Typical evaluation markers include the error's maximum, minimum, and root mean square value. A large reduction in error following calibration indicates the effectiveness of the calibration.

CHAPTER – 6

EMG SENSOR

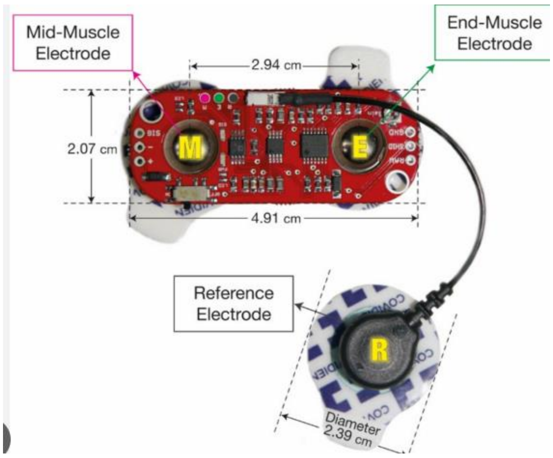

Figure – 5: EMG Sensor

Electromyography (EMG) sensors are pivotal tools in both medical and research fields, designed to measure the electrical activity produced by skeletal muscles. These sensors work by detecting voltage differences generated when muscles contract, translating these signals into data that can be analyzed to understand muscle function and health. Surface EMG sensors, the most commonly used type, consist of electrodes placed on the skin over the muscle of interest. The application of EMG sensors spans various domains. In clinical settings, they are instrumental in diagnosing neuromuscular disorders, aiding in the assessment of conditions such as carpal tunnel syndrome and amyotrophic lateral sclerosis (ALS). By analyzing the electrical activity patterns, healthcare professionals can pinpoint abnormalities in muscle function, facilitating accurate diagnosis and treatment planning.

In sports science and rehabilitation, EMG sensors provide insights into muscle activation patterns, helping athletes optimize their performance and prevent injuries. Physical therapists use EMG data to design and monitor rehabilitation programs, ensuring that exercises target the correct muscles and are performed correctly.

Despite their advantages, EMG sensors come with challenges. Accurate measurement requires proper electrode placement and skin preparation to minimize noise and interference. The signals can be affected by various factors, including movement artifacts and electromagnetic interference, necessitating advanced signal processing techniques.

Overall, EMG sensors are invaluable in enhancing our understanding of muscle dynamics, contributing to advances in medical diagnosis, sports performance, and rehabilitation. Their ability to provide real-time, non-invasive insights into muscle activity makes them a crucial component in modern biomedical technology.

CHAPTER – 7

COMPARATIVE STUDY

Inertial Measurement Units (IMUs), accelerometers, and Electromyography (EMG) sensors are critical components in modern sensing technologies. These sensors provide invaluable data across a broad range of applications, from robotics and consumer electronics to medical diagnostics and sports science. Understanding their working principles, interfacing methods, calibration requirements, and data characteristics is essential for effectively integrating these sensors into various systems.

7.1 Inertial Measurement Units (IMUs)

Working Principle

IMUs integrate multiple sensors, typically including accelerometers, gyroscopes, and sometimes magnetometers, to measure specific force, angular rate, and orientation. The accelerometer measures linear acceleration, the gyroscope measures angular velocity, and the magnetometer measures the magnetic field, aiding in orientation tracking.

Interfacing

IMUs are usually interfaced with microcontrollers or computer systems through communication protocols such as I2C, SPI, or UART.

I2C: Uses two wires (SDA and SCL) for short-distance communication.

SPI: Employs four wires (MISO, MOSI, SCK, and SS) for higher data rates.

UART: Utilizes two wires (Tx and Rx) for serial communication, often suitable for long distances.

Calibration

Calibration is essential for accurate measurements and involves:

Bias Calibration: Corrects constant offsets in sensor readings.

Scale Factor Calibration: Ensures sensor output matches expected values.

Alignment Calibration: Aligns the sensor axis to a known reference frame.

Data Characteristics

Accelerometer Data: Measured in meters per second squared (m/s^2) or g-forces (g).

Gyroscope Data: Measured in degrees per second (°/s) or radians per second (rad/s).

Magnetometer Data: Measured in microteslas (µT) or gauss.

7.2 Accelerometers

Working Principle

Accelerometers measure the rate of change of velocity (acceleration) of an object. They typically utilize microscopic crystals that generate a voltage when a force is applied, converting mechanical motion into an electrical signal.

Interfacing

Accelerometers often use I2C, SPI, or UART protocols, and may also output analog signals that can be read by an analog-to-digital converter (ADC) in a microcontroller.

Calibration

Static Calibration: Involves placing the accelerometer in known orientations and adjusting the output to match expected values.

Dynamic Calibration: Requires moving the accelerometer through known accelerations and adjusting the output.

Data Characteristics

Sensitivity: Typically measured in mV/g or LSB/g (least significant bit per g).

Range: Common ranges include ±2g, ±4g, ±8g, and ±16g.

Noise: Measured in µg/√Hz, representing the noise level.

7.3 Electromyography (EMG) Sensors

Working Principle

EMG sensors measure the electrical activity produced by skeletal muscles. Surface EMG sensors use electrodes placed on the skin to detect voltage differences generated by muscle contractions.

Interfacing

EMG sensors output analog signals read by an ADC in a microcontroller. The setup typically includes:

Electrodes: Detect electrical activity on the skin.

Amplifier: Boosts the small EMG signal to a measurable level.

Filters: Remove noise and unwanted frequencies.

Calibration

Calibration involves ensuring proper electrode placement and skin preparation to minimize noise and artifacts. This includes:

Skin Preparation: Cleaning the skin to reduce impedance.

Electrode Placement: Correctly positioning electrodes to capture muscle activity.

Signal Conditioning: Adjusting gain and filtering parameters.

Data Characteristics

Amplitude: Measured in microvolts (µV), reflecting muscle electrical activity.

Frequency: Muscle activity typically ranges from 10 Hz to 500 Hz.

Noise: Signal-to-noise ratio (SNR) is crucial for accurate readings.

CHAPTER – 8

CONCLUSION

IMUs, accelerometers, and EMG sensors are essential tools in modern technology, each with unique working principles, interfacing methods, calibration needs, and data characteristics. IMUs provide comprehensive motion tracking and orientation data, accelerometers offer precise measurements of linear acceleration, and EMG sensors deliver detailed insights into muscle activity. Proper calibration and interfacing are crucial for accurate data collection, which in turn enhances the functionality and reliability of the systems these sensors are integrated into. Understanding these aspects ensures the effective use of these sensors in diverse applications, from consumer electronics and robotics to medical diagnostics and sports science.

8.1 REFERENCES

https://www.jouav.com/blog/inertial-measurement-unit.html

https://medium.com/@ericco741/imu-calibration-method-and-calibration-process-e111dead7323

https://www.seeedstudio.com/blog/2019/12/29/what-is-emg-sensor-myoware-and-how-to-use-with-arduino/

Wolf, M., Rupp, R., & Schwarz, A. (2024). Decoding of unimanual and bimanual reach-and-grasp actions from EMG and IMU signals in persons with cervical spinal cord injury. *Journal of Neural Engineering*, *21*(2), 026042.

Senthilvel, A., Sankaragomathi, B., Manju, M., Vijayalakshmi, M., & Sujeeth, K. (2024). Analysis of Gait Dynamics using Motion and EMG Sensors.