Mechatronics Education: Exploring Inertial Measurement Units Through Hands-on Learning

Mohammadianaftah, Nafiseh and Wilson, Sara E.
Mechanical Engineering, University of Kansas

Abstract

Inertial Measurement Units (IMUs) are commonly used in many devices, from exercise tracking watches and cell phones to aircraft and space vehicles. These sensors include triaxial accelerometers, gyroscopes, and magnetometers. In a mechatronics course taken by upper level undergraduates and graduate students, a set of laboratory exercises was created to provide hands-on experience and practical exposure to the operation and applications of Inertial Measurement Units. The three week laboratory workshop was designed to familiarize students with the hardware and software aspects of the IMU sensor and filtering techniques, enabling them to effectively utilize their ability to apply this knowledge to tangible and innovative projects. The aim of this 3-week laboratory workshop was to educate students on the basics of the IMU sensor, its features, and how to utilize it alongside signal processing and filtering techniques to extract reliable data. The results demonstrate that the students gained a fundamental understanding of the IMU sensor and were able to apply their knowledge to practical projects.

Keywords

Inertial Measurement Unit, Instrumentation, Signal Processing, Graduate Student Paper

Introduction

An Inertial Measurement Unit, or IMU, is composed of a triaxial accelerometer, a triaxial gyroscope, and a triaxial magnetometer. IMU sensors are essential in position tracking applications and are found in diverse fields such as medicine, flight controls, and navigation. Chattha et al [1] showed IMUs can be cost-efficient, mass-produced and are now present in everyday gadgets such as fitness trackers. In historical context, Martin et al [2] mentioned the Apollo spacecraft relied on IMU technology to precisely track both its position and orientation during its lengthy journey to the moon. As landmarks in space are scarce, using fixed stars for guidance proved challenging. Nevertheless, the onboard IMU effectively enabled safe navigation to the moon's surface without relying on such landmarks. Today, IMUs continue to play a vital role in modern motion tracking projects. The economical sensors are lightweight, consume low power, and can be integrated into a range of devices. However, Garcia-Hernández et al [3] demonstrated that they can produce measurements with considerable noise.

IMU sensors are often used in these devices to assess sensor orientation and displacement, which are not directly measured by the sensor. The process to determine orientation and position requires additional, non-trivial, processing steps. The triaxial accelerometer data reflects both the acceleration of the sensor and the gravity vector. In a stationary situation, the accelerometer can be used to determine the direction of the gravity vector. In combination with the magnetometer (which reflects magnetic north in the absence of other electromagnetic noise), sensor orientation can be assessed. However, electromagnetic noise and sensor motion would impact this method of determining sensor orientation. The triaxial gyroscope reflects rotational velocity of the sensor. Integration of this data can also be used to determine sensor orientation as well. However, this method of determining orientation can be subject to signal noise and integration drift which increases its inaccuracy over time. Combining these two methods (through sensor fusion) is often used to obtain orientation data. Obtaining displacement from IMU sensors requires removing the gravity vector from the accelerometer data and double integration of that acceleration. To remove the gravity vector, sensor orientation is used, so error in sensor orientation can impact the accuracy or displacement calculation. The double integration can also be impacted by integration drift.

In a course focused on mechatronics, a laboratory on IMUs allows for practical, hands-on exploration of a number of general mechatronics topics including:

1. Serial communications with sensors
2. Sensor calibration
3. Filter design
4. Signal noise and signal integration
5. Sensor accuracy and repeatability

Additionally, a laboratory on IMUs allows for sensor specific exploration of:

1. Sensor fusion (fusion of the orientation derived from the accelerometer/magnetometer and from integration of the gyroscope)
2. Integration drift
3. Filter design (Kalman filter) for improving integration drift errors

In this paper, we will describe a laboratory created to allow students to work with an IMU to achieve several learning objectives. These learning objectives include:

1. Students will be able to collect data from an IMU sensor using serial communication.
2. Students will be able to find the orientation of the moving object using an IMU.
3. Students will be able to apply basic filtering methods to minimize the signal noise.

Course

The course is an introductory course in mechatronics taken by upper level (junior and senior) undergraduates in Mechanical Engineering and graduate students from several departments (Mechanical Engineering, Aerospace Engineering, and Bioengineering). The course is taught as a night course, meeting for 150 minutes once a week. Most of the students start this course with some familiarity with programming but not necessarily in the same languages. The first part of the course covers the fundamentals of programming an Arduino Uno in C++, communication with sensors and motors, and basics of filters (low, high and band pass). Prior to the IMU laboratory, the students work with ADXL335 triaxial accelerometer [4]. In these exercises, the students learn about the impact of gravity on the accelerometer signal and learn how to use Butterworth filters in MATLAB to remove signal noise.

Hardware and Software

The required hardware for this laboratory workshop was:

1. BNO055 IMU sensor (Adafruit, New York, NY)
2. Arduino microcontroller (Arduino Ivrea, Italy) or similar microcontroller
3. 4 jumper wires
4. 1 breadboard

For software, this laboratory workshop used:

1. Arduino IDE (Arduino Ivrea, Italy) – An open-source C++ based integrated development environment for microcontrollers
2. Matlab (Mathworks, Natick, MA)

In this laboratory, the students utilize the Arduino Uno microcontroller and breadboard, which they have acquired as part of their classroom supplies. Additionally, each group is provided with a BNO055 IMU sensor to work with. For the setup, they are required to wire their circuit as shown in Figure 1.

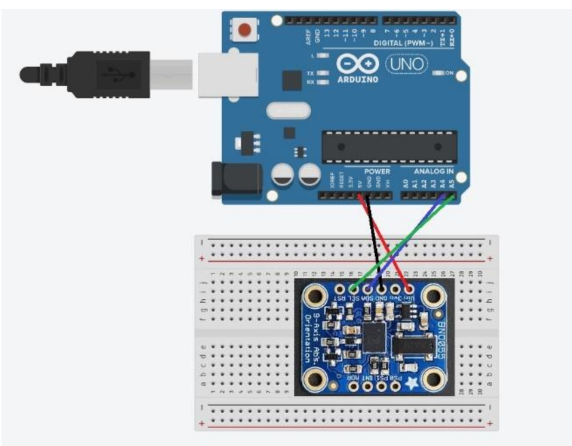

Figure 1, Wiring of the BNO055 IMU sensor to the Arduino Uno Microcontroller

Sensor

The BNO055 is a cost efficient IMU sensor developed by Bosch Sensortec and marketed by Adafruit. This 9 DOF sensor can be run with the BSX3.0 FusionLib software or with Arduino or Python based libraries [5]. It can operate in both fusion and non-fusion modes, offering flexibility to cater to diverse task requirements. Output fused data include the linear acceleration, rotation vector, orientation in Euler angles, orientation in quaternions, gravity vector, and heading. Students are given instruction in using the I2C interface for serial communication to the Arduino Uno. For the Arduino Uno, the SDA pin is wired to analog pin 4 and the SCL pin is wired to analog pin 5.

The first task was to make the students familiar with the manufacturer's datasheet and software package. The sensor offers a range of output signals that can be easily selected by choosing the appropriate operation mode. The students are encouraged to use the NDOF operation mode because the fusion of all three sensors (accelerometer, magnetometer and gyroscope) offers several advantages, including fast calculations leading to a high output data rate, and enhanced robustness against magnetic field distortions. In this mode, the manufacturer mentioned the fast magnetometer calibration is activated, ensuring a swift calibration of the magnetometer and achieving higher output data accuracy [5].

Elements of an IMU: Accelerometer

An explanation of how accelerometers function can be summarized as follows: These devices measure acceleration along a single axis and come in various types, with cheaper ones often utilizing miniature cantilever beams and proof masses. When subjected to acceleration, as shown in Figure 2, the beam deflects which can be quantified using capacitive circuits to determine the acceleration value. Some higher-cost accelerometers may implement piezoelectric materials. It's important to clarify that accelerometers measure proper acceleration or specific force. Husni et al [6] demonstrated that accelerometers respond to any motion or vibration resulting from movements starting from a stationary position. The concept of a simple accelerometer can be realized by attaching a mass to a spring and measuring its deflection using Newton's second law. The accelerometer's measurement model includes noise and bias terms [7]. Unlike rotational rates that directly measure body accelerations, we must explicitly account for the influence of gravity when using accelerometers in a gravity field. Hence, achieving an accurate orientation estimate becomes vital for precise position calculations. To convert the measured specific force into acceleration, we must ensure that the direction of gravity is accurately accounted for. Even a minor orientation error can lead to erroneous acceleration interpretations.

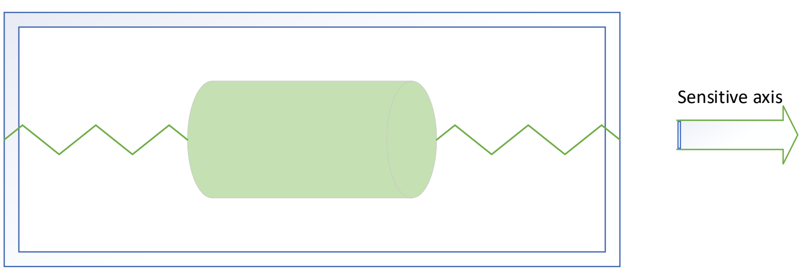

Figure 2, Simple Accelerometer Model

Elements of an IMU: Gyroscope

The term "gyroscope" originates from the Greek words "Gyros," meaning circle, and "Skopos," meaning to observe [8]. In historical contexts, a gyroscope was a spinning disk with angular momentum, providing resistance to changes in orientation. Traditional gyroscopes typically consist of a spinning wheel that resists alterations in its angular momentum vector relative to inertial space as it is demonstrated in a simple sketch in Figure 3. In modern times, gyroscopes measure angular velocity vector (rad/s). The angular rotation rate, obtained from all three gyroscopes, represents the body frame's angular velocity relative to an inertial frame, expressed in the body frame. As shown by Fuchs [9], gyroscope data is crucial as it supplements the accelerometer data, which has a delayed signal due to averaging. Despite their significance, gyroscopes do have some drawbacks. The existence of moving parts causes friction leading to drift, which is a primary disadvantage. Additionally, noise is inevitable in their functioning.

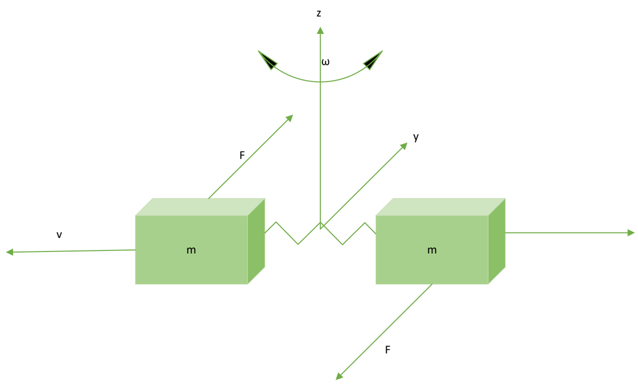

Figure 3,Simple Gyroscope

Elements of an IMU: Magnetometer

A magnetometer is a sensor designed to gauge both the intensity and orientation of a magnetic field. Numerous types of magnetometers exist, with MEMS magnetometers predominantly utilizing magnetoresistance as the means to assess the magnetic field in their vicinity. These sensors are used, primarily to find the direction of earth's magnetic field. However, they can also pick up electromagnetic noise in the environment.

Calibration

Three main types of calibration are: 1. intrinsic calibration which involves sensor-specific parameters, 2. extrinsic calibration, which deals with sensor positioning and orientation on the object, and 3. temporal calibration, which addresses the time offset between different sensor measurements [10]. The self-calibration process in the BNO055 involves continuous monitoring and compensation for various sensor errors and biases. During the initialization phase, the sensor gathers data from its built-in sensors and utilizes algorithms to estimate and calibrate the sensor's internal parameters. This includes calibrating the accelerometer to account for any misalignment or sensitivity differences, compensating for gyroscope drift, and calibrating the magnetometer to adjust for any hard and soft iron interference. However, for educational purposes, the full calibration process was undertaken, despite the manufacturer's claim that the accelerometer and gyroscope are less susceptible to external disturbances. The calibration process involved implementing the appropriate code and performing specific movements to achieve full calibration. The sensor has four calibration statuses (0 to 3) for each of its sensors, as well as an overall system status. According to [5] status of 0 indicates no calibration, while 3 indicates full calibration.

The calibration process begins with running the appropriate calibration code which was provided to the students. The code to read the calibration status of the sensor is readily available in the library provided for the sensor. When you install the specific library for the sensor, you gain access to functions that allow you to easily retrieve and interpret the calibration status of the gyroscope, magnetometer, and accelerometer. To achieve the status 3 (full calibration), the sensor needs to undergo a calibration procedure. For gyroscope calibration, the sensor must be placed in a stable position and monitored until the number 3 is displayed in the serial monitor, signifying successful calibration. To attain a status of 3 for the magnetometer, the sensor should be subjected to a figure-8 motion parallel to a flat surface, allowing it to capture the necessary data points for accurate calibration. Full calibration of the accelerometer involves holding the sensor at both 0-degree and 45-degree angles from a level surface along all three axes, ensuring precise calibration for reliable data output. This procedure should be repeated until the calibration value of the sensor is 3.

Sensor fusion and filtering

Sensor fusion is the process of combining data from multiple sensors to obtain a more accurate estimate of the system state. Filtering is a technique used to process sensor data to remove unwanted noise or errors and obtain a more accurate estimate of the system state. Filtering can be used in conjunction with sensor fusion to improve the accuracy and stability of the system. In groups of four, the participants were given the assignment to collect data from the sensor and apply data filtering techniques [7]. Through this exercise, they gained a comprehensive understanding of the filtering process, particularly in working with raw data. They observed the presence of noise and recognized that attempting to process the data, particularly by integrating the accelerometer data to determine displacement, led to an escalation of drift.

Three Week Workshop

The IMU workshop takes place over the course of 3 weeks (150 minutes each week). The students work in groups of four on this project.

During the first week, the laboratory focused on the basics such as libraries, interfaces, and sensor calibration for the BNO055. The students are asked to wire the sensor using a breadboard and create code to read the sensor and send the data to the serial port. The students are also asked to write MATLAB code to read the serial port and display the data. They learned about various types of IMUs and some examples of their applications. The primary goal of this week was to provide a strong theoretical foundation for understanding how sensor data is collected.

Active Learning
The active learning topics for the first week included:

- Wiring The Arduino
- Serial Communication (UART Versus I2C)
- Adafruit BNO055 Library
- Calibration
- Reading Data

Exercises
After completion of the active learning component, students were asked to work with their group on two exercises:
- Level Sensor Using Fused Orientation Data From Sensor
- Accessing Gyroscope Data To Detect Tilting

During the second week, the students are introduced to the fundamentals of data processing and motion tracking. The students progressed to implementing small projects, such as determining the sensor's orientation while moving along a random trajectory. To enhance motion tracking accuracy, the implementation of filtering algorithms like low-pass and Kalman filters to reduce noise was discussed. Since the students had prior experience with MATLAB in other classes, this study provided an opportunity for them to work with their own data and process it.

Active Learning
During the second week, the following topics were discussed during the active learning component of the class:
- Representing Rotation In 3D (Direction Cosine Matrix, Euler Angles, Quaternions)
- Gravity Vector and Gravity Compensation
- Noise
- Fast Fourier Transform
- Filtering Algorithms

Exercises
The students were then asked to do the following exercises:
- Complete Week 1 Exercises
- Fall Impact Detection

The third and final week of the course aimed to reinforce the students' understanding of data filtering and processing. We explored filtering techniques and discussed how to find the optimal technique for specific applications. Moreover, the students used visualization tools to observe and analyze the orientation of the IMU as part of their projects. With the help of processing software and Web serial visualizer, they experienced a visual presentation of the numbers, however only a limited number of them worked on gravity compensation, while the others were asked to do the “unweighting” in the stationary position. This practical experience enhanced their ability to interpret and present results effectively.

Active Learning

The active learning component of the third week included coverage of:

- Sensor Fusion
- Kalman Filter
- Madgwick AHRS Algorithm
- DCM Complementary Filter

Exercises
The exercises for the third week included:

- Using Matlab's Complementary Filter and Euler Angle Conversion To Obtain Orientation (Figure 4)
- Removing Gravity from The Acceleration Data (Statically Or Dynamically)

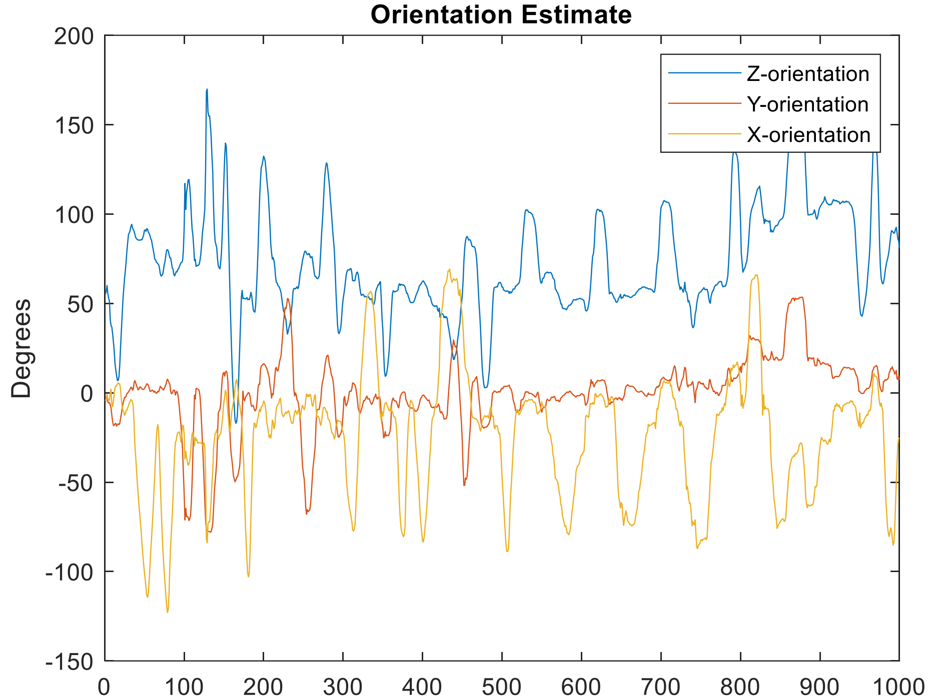

Figure 4, Filtered Orientation Estimation using Complementary Filter

By breaking down the course content into these three weeks, we ensured that each week's goals aligned with the corresponding sections on data processing, motion tracking, and filtering algorithms. This approach prepared them to tackle more intricate data processing tasks in their future endeavors.

Results

Based on the feedback and evaluation from the students, it is evident that they have developed the practical skills to code and program an IMU. They have demonstrated a good grasp of filtering techniques and its importance in data processing and sensor fusion for state estimation. However, some students expressed challenges with the mathematical aspect of the course, indicating a need for more in-depth explanations of the mathematical concepts involved.

Additionally, a few students found the provided templates, whether in the form of pseudo code or code snippets, limiting their engagement with the tasks. They expressed a desire for a more comprehensive exploration of coding principles and the underlying mathematical foundations of the sensor module, as well as real-world applications. Throughout the workshop, the students successfully implemented the learned concepts and gained a better understanding of how to utilize the BNO055 sensor in various applications. It is encouraging to see that this workshop has inspired them to explore further and undertake more advanced projects using the BNO055 sensor and signal processing techniques.

Midway through this workshop, the students were asked to answer two questions to gauge their understanding of the sensor and identify potential challenges. The answers were used to address the challenges and enhance the learning experience.

The first question was “What are the first steps to use the BNO055?”. 79% of the participants mentioned that the first step is to install libraries available from the Arduino Library Manager or GitHub. 11% chose calibrating the sensor and the rest emphasized the importance of following the manufacturer's recommended power-up and initialization sequence or running a simple test program that reads the sensor data. From these answers it appeared that students had a good grasp of the steps to work with IMU sensors.

When asked about the common pitfalls or issues when using the new sensor such as BNO055, 54% of the group pointed out the calibration or bias errors, 21% of the participants highlighted incorrect data format or scaling as an issue, 18% mentioned incorrect wiring and a few believed sensor drift or noise is the main issue. It is worth noting that while many students had theoretical knowledge about using a new sensor, most of the class encountered challenges when it came to implementing the basic steps initially.

Conclusion

The three-week workshop facilitated the understanding of various topics, such as sensor calibration, motion tracking, and filtering algorithms. By working with real-world data and projects, students gained proficiency in coding and programming the IMU, interpreting sensor data, and applying filtering techniques to minimize noise. The course aimed to educate students on the fundamentals of IMUs, their features, and their practical applications through a series of laboratory exercises. Although the course received some positive feedback, there is room for improvement, particularly in providing more in-depth mathematical explanations, especially concerning filtering methods.

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Nafiseh Mohammadianaftah

Nafiseh Mohammadianaftah is a PhD candidate at the university of Kansas and currently working on understanding the etiology of injury in the lumbar spine and working with physical therapists to develop novel devices and computational models to assist in injury prevention and rehabilitation.

Sara Wilson

Sara Wilson is an associate professor of the mechanical engineering and a core faculty of the bioengineering department at the university of Kansas. Her research focus is on the neuromuscular control of human motion using engineering principles from control theory and dynamics. She is also active in teaching and development of educational tools in responsible conduct of research for graduate students in engineering.