ECE 445 - Senior Design Project Proposal

Extending IMU Degrees of Freedom for Pose Estimation Using AI on Chip
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Team 71
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1. Introduction

1.1 Problem

An Inertial measurement unit (IMU) is a combination of sensors that collects data based on movement. IMU's normally include an accelerometer and a gyroscope which track the specific acceleration and the angular acceleration of the object.

The sensors are:

- Accelerometers: Used to measure linear acceleration in three dimensions. This information can be used to estimate the velocity and position of the object over time.
- Gyroscopes: Used to measure angular velocity in three dimensions. This information can be used to estimate the orientation of the object over time.
- Magnetometers: Used to measure the direction of the Earth's magnetic field. This information can be used to determine the orientation of the object with respect to the Earth's magnetic field, which can be used to correct errors in the orientation estimate obtained from the gyroscopes.

IMU's are used in a wide range of applications but they are really important in the medical field and in consumer electronics.
Some example applications include movement tracking on patients to detect disorders or even tracking movement in your cell phone to get its orientation.

9DOF IMU sensors can be found for as low as $10-$20 for basic models, but these sensors have lower accuracy. For projects that require greater accuracy, the cost can go up to 300$ (https://x-io.co.uk/ngimu/) and this limits projects that require multiple such devices.

1.2 Solution

An AI on chip solution may have the potential to reduce the cost of 9DOF IMU sensors by enabling the integration of multiple sensors and processing functions onto a single chip, which can simplify the design, reduce the bill of materials, and lower the manufacturing costs.

By leveraging AI algorithms among others, an AI on chip can enable 9DOF IMU sensors to perform advanced sensing and processing tasks on-device, reducing the data transmission requirements and minimizing the need for external computing resources.

Our solution is to take a cheap 6 DOF IMU and combine it with a RNN that we train to calculate the other 3 DOF that a magnetometer normally provides. We will then take this AI model and put it onto a chip. The AI on chip will work together with the 6DOF IMU to emulate a 9 DOF IMU in a handheld format.

1.3 Visual Aid

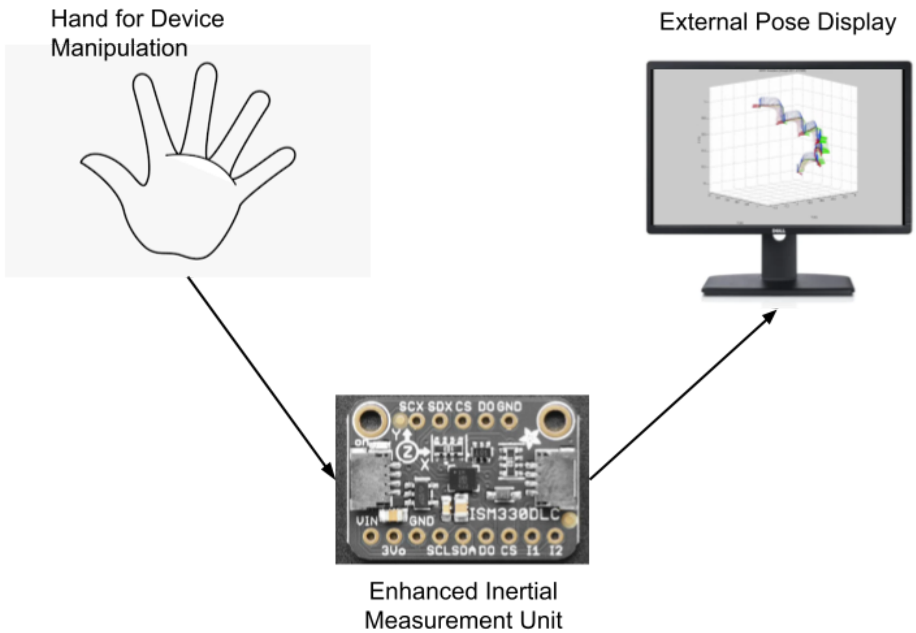


Figure 1. Visual Aid

1.4 High-Level Requirements List

- The output of the AI on chip should have increased accuracy when compared to the raw output of the IMU
- There is a real time display of the Pose of the IMU
- There is data with which we can compare the performance of the different enhancements and identify which ones work better than others

1.5 Block Diagram

The proposed project comprises of two block diagrams, each representing a different stage of the project. The first block diagram depicts the initial deliverable, which is intended to serve as the minimum viable product for the project. This block diagram focuses on testing various algorithms on the NVidia Jetson, which will be used to process the data generated by the IMU.

The separation of the Jetson from the rest of the subsystems enables us to quickly and easily deploy different algorithms without having to make any changes to the other subsystems.

The second block diagram represents the reach goal of the project. After evaluating the performance of various algorithms, we aim to integrate the most promising ones into the PCB. This could be accomplished through hardware implementations using filters or onto a FPGA unit. In this design, the data processing will be directly connected to the IMU, eliminating the need for an intermediary control unit. However, the control unit will still play a critical role in managing the flow of data and providing the same functionalities as in the initial deliverable design.

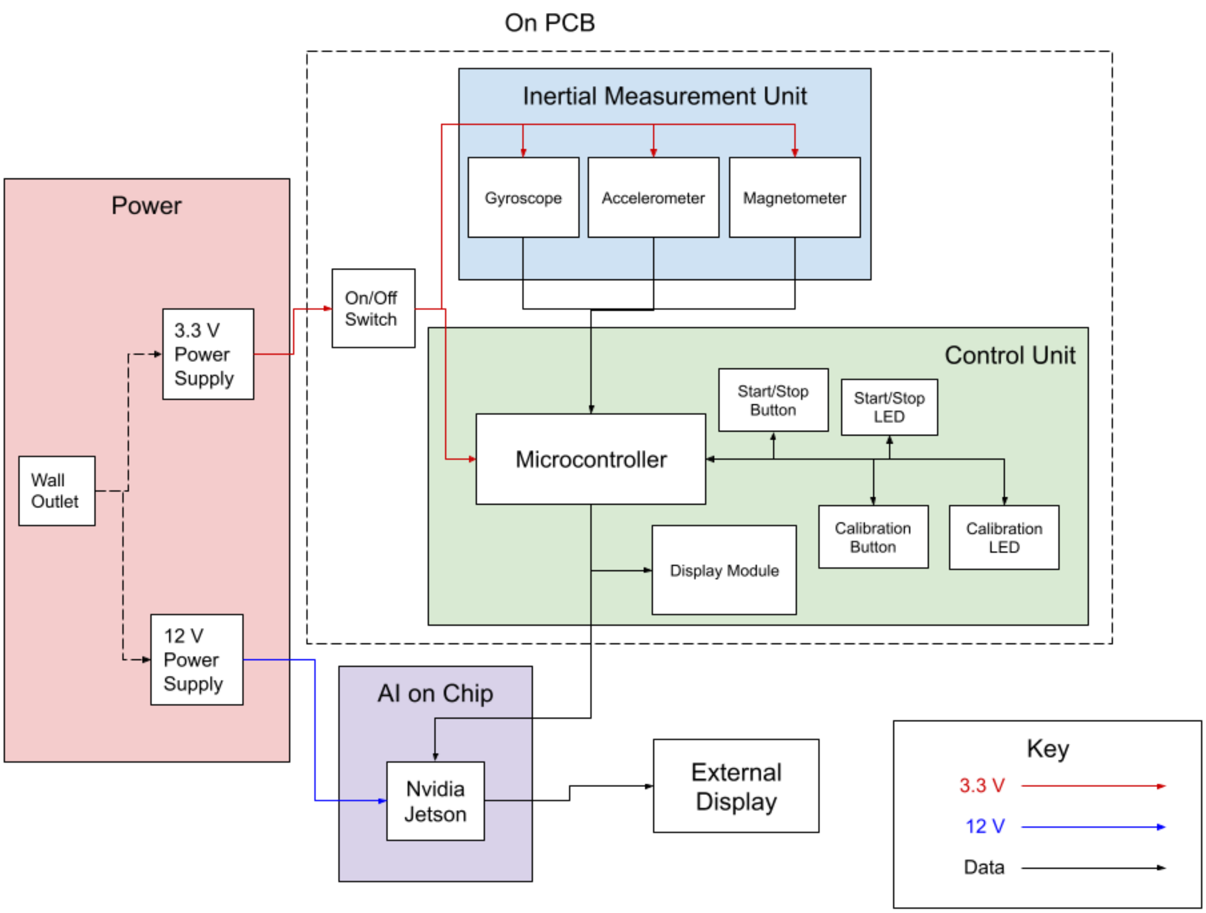


Figure 2. Initial Deliverable Block Diagram

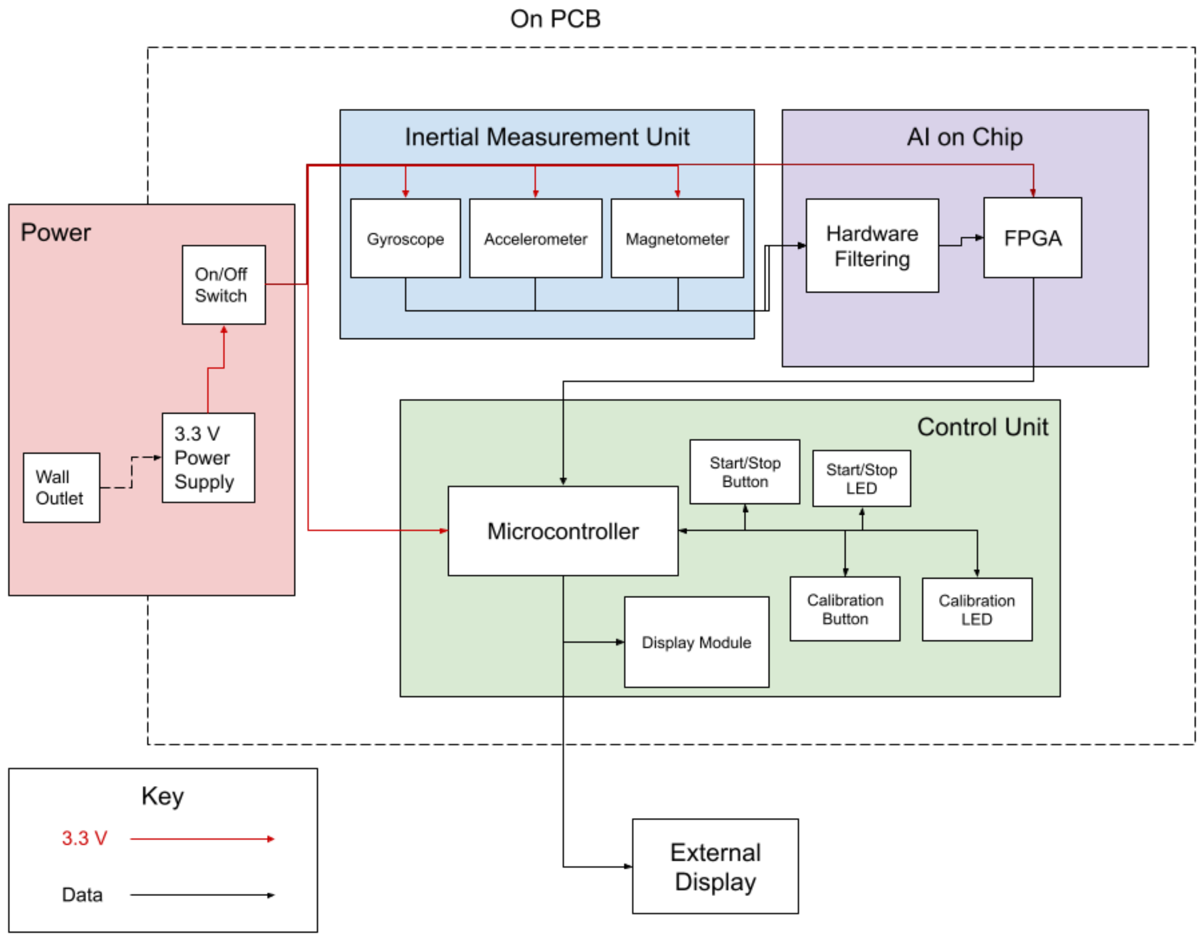


Figure 3. Reach Design with Hardware Accelerated AI Block Diagram

2. Subsystem Overview

2.1 Subsystem 1: Inertial Measurement Unit

This subsystem will be an 6 DOF IMU that we acquire from a third party distributor. We will have to research what the IMU will output and how to connect to it as well as how to calibrate the IMU. We are considering using an Adafruit ISM330DHCX as the IMU ($20) and the MPU-6050 (3$).
https://www.adafruit.com/product/4502
https://www.amazon.com/HiLetgo-MPU-6050-Accelerometer-Gyroscope-Converter/dp/B01DK83ZYQ?th=1

2.2 Subsystem 2: Control Unit

The Control Unit is a critical component of our design, tasked with interfacing with the IMU and directing the raw data it outputs. Communication between the Control Unit and IMU will be established using the I2C data protocol, and the Control Unit will also be responsible for calibrating the IMU. Additionally, the microcontroller will be connected to a USB port for interfacing with the NVidia Jetson in the deliverable model and for communication with an external display in the reach model. The Control Unit, as the central entity for data flow management, enables us to incorporate other control components such as a button for activating and deactivating data flow and a button for calibrating the IMU to determine the error size.

2.3 Subsystem 3: Position Estimation using AI on Chip

AI on chip either through Nvidia Jetson or fpga that will take the output of the IMU and predict what the orientation of the device will be.
We will be deploying a CNN model to begin with, however we will be looking into the following algorithms as well: Accelerometer Inclination, Gyroscopic Integration, Complementary Filter, Kalman Filter, Digital Motion Processing, Madgwick Filter, Mahony Filter. The hardest challenge of this project will be the hardware acceleration of these algorithms and processing data while dealing with noise.
https://ieee-dataport.org/open-access/estimating-relative-angle-between-two-6-axis-inertial-measurement-units-imus.

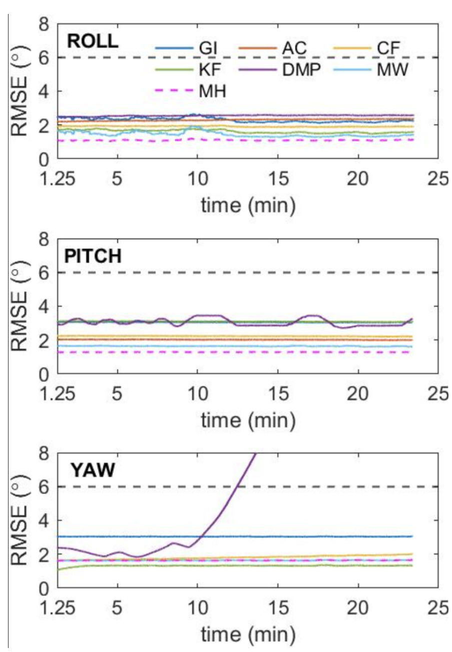
Standard Algorithms:

We will begin by implementing 3 of the 7 standard algorithms selected based on the performance seen below.

We will be implementing the Kalman Filter, Madgwick Filter, and Mahony Filter.

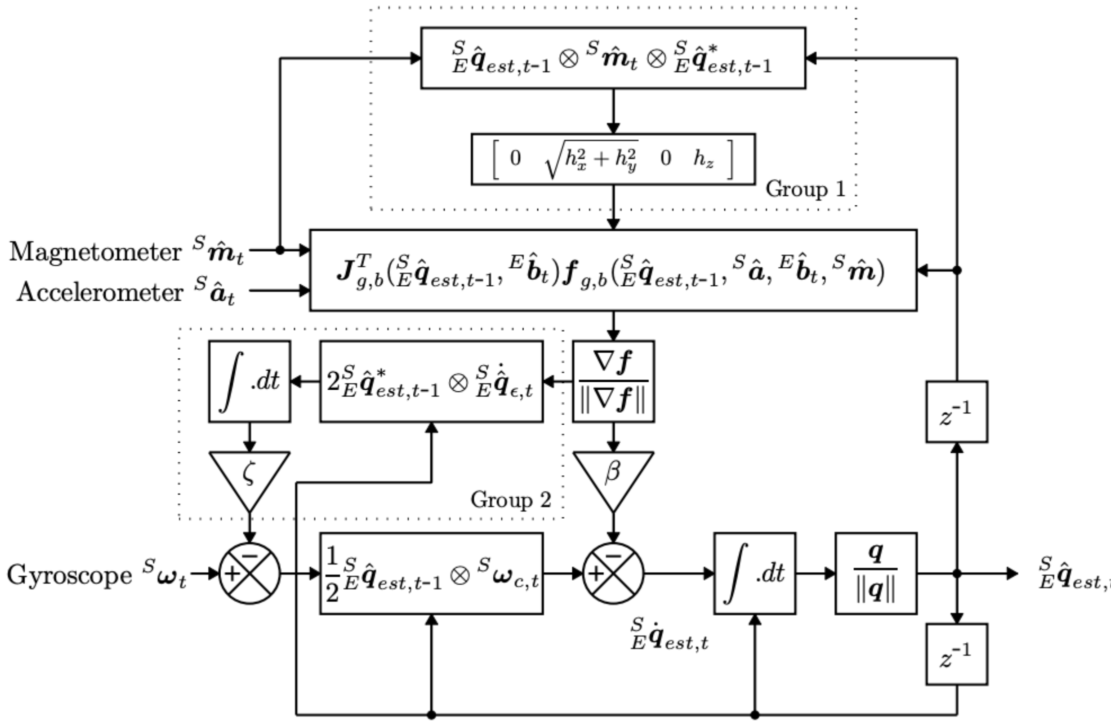
Kalman Filter:

A Kalman filter is a type of mathematical algorithm that is used to estimate the state of a system over time. In the context of orientation tracking, a Kalman filter can be used to estimate the orientation of an object by combining the measurements from an accelerometer and a gyroscope.



Madgwick Filter:

The Madgwick filter is a type of complementary filter used to estimate the orientation of an object.



Here, the block diagram represents the complete orientation filter for an MARG implementation including magnetic distortion (Group 1) and gyroscope drift (Group 2) compensation

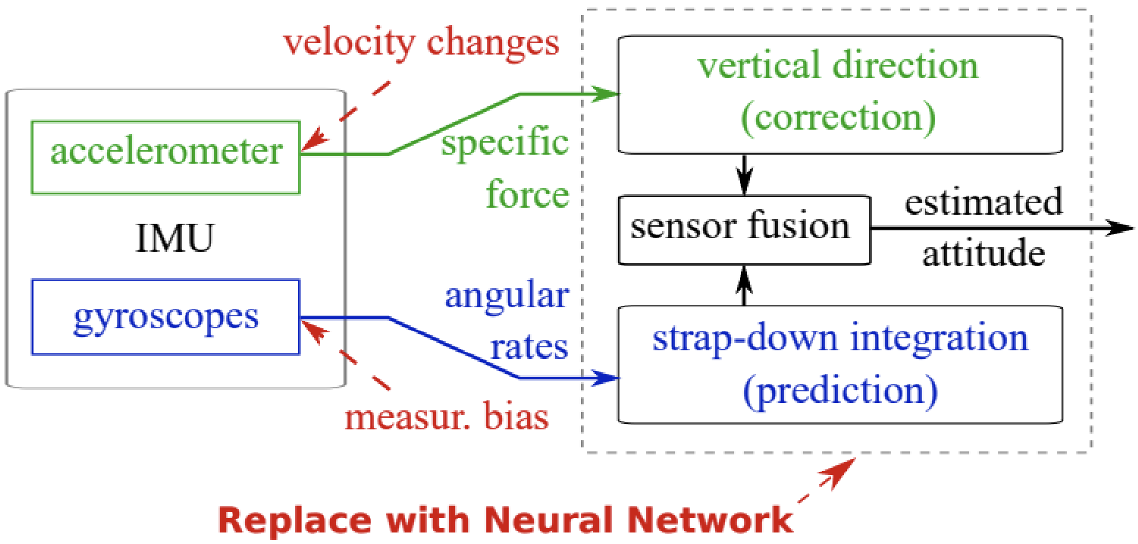
We will try to implement the following code (https://github.com/bjohnsonfl/Madgwick_Filter/blob/master/madgwickFilter.c)

Mahony Filter:

The Mahony filter is a type of complementary filter used to estimate the orientation of an object. The Mahony filter is known for its high accuracy and fast processing times.

We will try to implement the following code (https://github.com/gaochq/IMU_Attitude_Estimator/blob/master/src/Mahony_Attitude.cpp)

Using Deep Learning



(https://arxiv.org/pdf/2005.06897.pdf)

When a large range of different dynamic and static rotational and translational motions is considered, the attainable accuracy is limited by the need for situation-dependent adjustment of accelerometer and gyroscope fusion weights. We investigate to what extent these limitations can be overcome by means of artificial neural networks and how much domainspecific optimization of the neural network model is required to outperform the conventional filter solution.

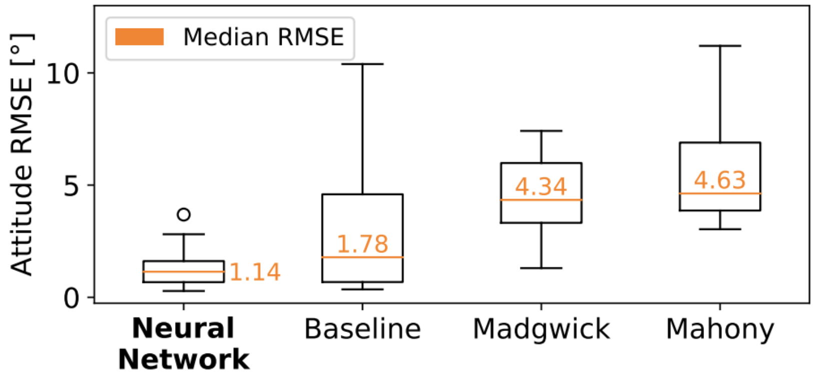
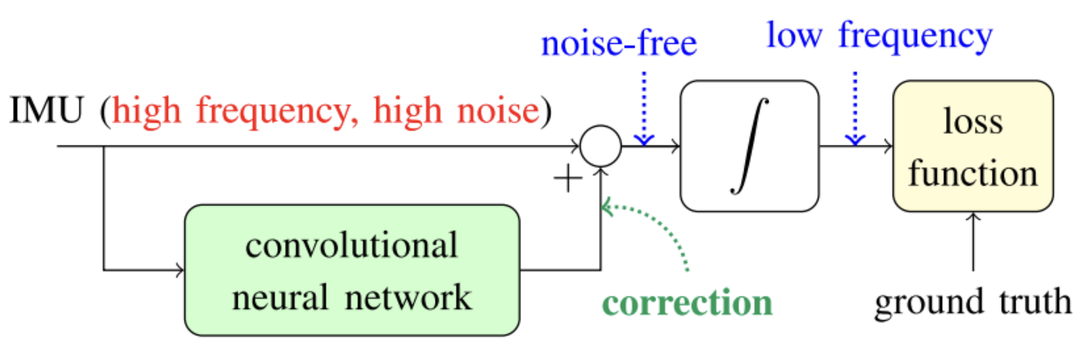
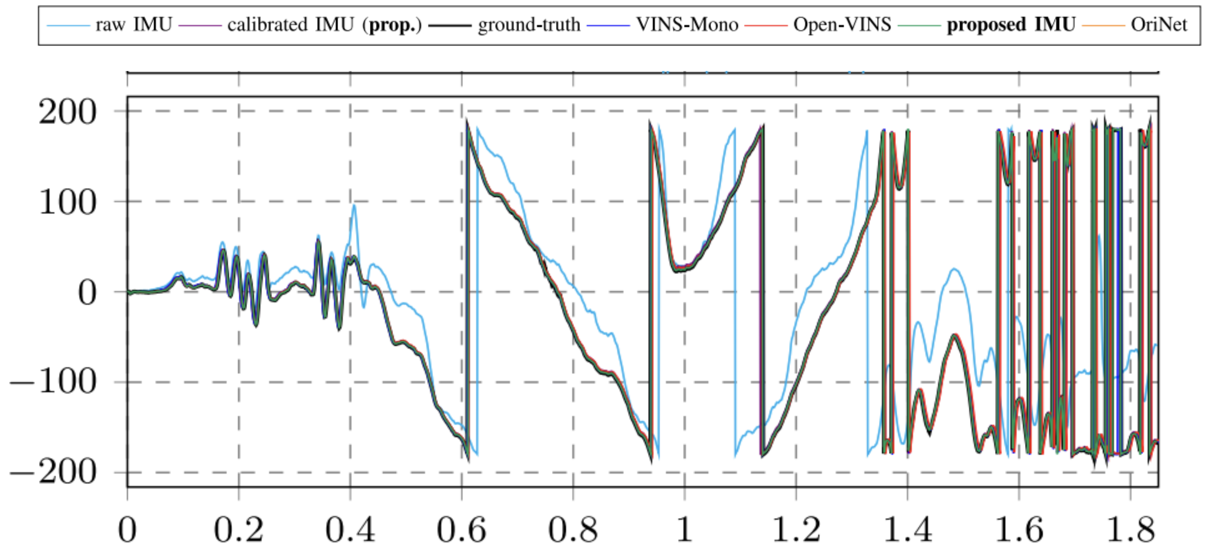


Fig. 8. RMSE comparison between the best neural network, the baseline filter [4], and two open-source available filter algorithms [31]. Across all types of motions, the proposed neural network achieves clearly smaller median and variance than the conventional filters. Details are presented in Fig. 9.

We can see based on results from papers that using a RNN or CNN minimizes the RMSE and provides promising results.
We will begin by implementing the following code (https://github.com/mbrossar/denoise-imu-gyro) for Denoising IMU Gyroscopes for Open-Loop Attitude Estimation.



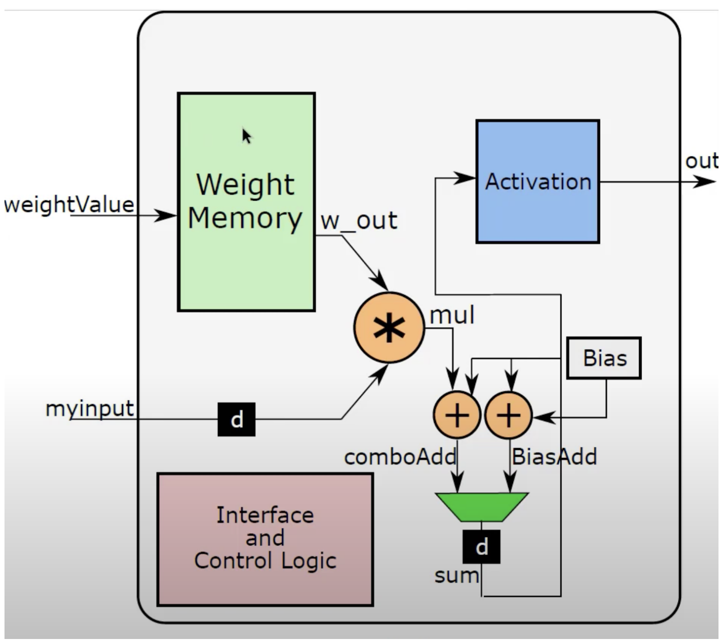
(https://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=9119813)



This paper has promising results and we will compare the RMSE with that obtained by the standard algorithms. If this approach is significantly better, we will move onto accelerating this using hardware optimizations.

Neural Networks on FPGA:

The CNN is costly and will reduce the frequency of output. Therefore our reach goal is to deploy the CNN on an FPGA.



(https://www.youtube.com/watch?v=a2wOjxRf_xg&list=PLJePd8QU_LYKZwJnByZ8FHDg5I1rXtcIq&index=2)

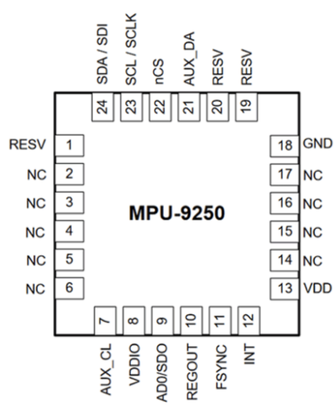
2.4 Subsystem 4: Power Supply

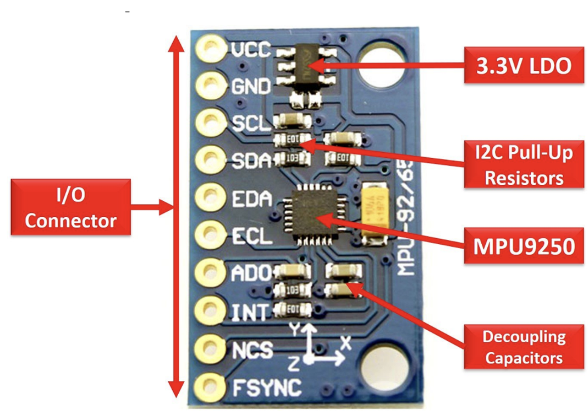
The Power Subsystem will serve as the primary source of energy for the various components in our design, including the IMU, microcontroller, AI on chip, and any hardware filters. This subsystem will perform the conversion of AC power from the wall outlet to DC power and regulate the DC power to meet the varying voltage requirements of the different components. The Power Subsystem must be properly integrated with all other subsystems to ensure seamless operation.

3. Subsystem Requirements

3.1 Subsystem 1: Inertial Measurement Unit

This subsystem will be an 6 and 9 DOF IMU. We will connect this IMU to the Microcontroller to get values from the accelerometer, gyroscope and the magnetometer if available. We will be using the I2C serial communication to get values from the IMU.





3.2 Subsystem 2: Control System

The Control Subsystem is designed to manage the flow of data within the project and comprises a microcontroller, USB port, power on/off switch, start/stop button, and LED indicators for controlling data recording, and a button and LED for calibrating the IMU. The microcontroller used in this subsystem is the ATtiny device. The power on/off switch serves as the main power switch for the entire PCB board. The start/stop button enables the user to initiate and halt data transfer to the USB port, ensuring data recording is only performed when desired. The calibration button controls the IMU calibration process and indicates the start and end of calibration in the recorded data, allowing for comparison of the error in positions. Communication between the microcontroller and the IMU is facilitated through I2C protocol and the collected data is sent to the USB port after formatting. The USB port serves as the interface between the control subsystem and the Nvidia Jetson in the final product, and with an external computer for display in the Reach model. The Control Subsystem is powered by a 3.3V voltage supply from the Power Subsystem.

3.3 Subsystem 3: AI on Chip

Deliverables: Run 3D position estimation on the Nvidia Jetson using the data from the Microcontroller. We run the position estimation calculation after the values have been collected to display the output on a screen. Our goal is to show a live output of the position estimation.

Reach: Deploy the Neural Network using an FPGA for hardware acceleration.

3.4 Subsystem 4: Power Supply

The Power Subsystem must be capable of providing a stable voltage output of at least 3.3V to all the components located on the Printed Circuit Board (PCB). The Power Subsystem must be designed to handle the current requirements of various components including the ATtiny microcontroller which requires less than 5mA, the IMU which is expected to draw less than 50mA of power, and in the reach plan, the hardware-accelerated AI implementation that may include a Field-Programmable Gate Array (FPGA) with varying current consumption based on the selected FPGA model. To accommodate the consumer-grade nature of some components, a voltage tolerance of +/- 0.2V is targeted during operation. Additionally, the Power Subsystem must provide power to the NVidia Jetson in the reach model, which requires a 12V power supply and has a power consumption range of 7.5 to 15 watts. This power requirement will be met using a premade power brick that is included with the Jetson.

4. Tolerance Analysis

The rate of communication between the IMU and Microcontroller may not be as high as given on the IMU documentation. Furthermore, the frequency may be further reduced between the Jetson Board and the Microcontroller.
The time taken by the forward function for a CNN or the inference time for a transformer may be too high causing issues on demoing the 3D position estimation at a high frequency. We may try to accelerate this through hardware but the results are not guaranteed.
Deploying the CNN on the FPGA will be quite challenging and we may not get the accelerated results we are looking for. That's why we have it under a reach goal.

5. Ethics and Safety

In accordance with the IEEE Code of Ethics, it is of utmost importance to maintain originality and integrity in the project ideas and research process. Any sources used during the research must be properly cited and credited to avoid plagiarism (IEEE Code of Ethics II.5). Our project is aligned with the ongoing efforts in improving the accuracy of IMU sensors, and while referencing relevant research papers, all sources used will be properly cited and credited. Our project aims to differentiate itself from existing technologies by utilizing unique methods of implementation. Furthermore, the IEEE Code of Ethics I.5 requires that all claims and estimates be honest and realistic. In the context of our project, we strive to enhance the precision of IMU data output to the best of our abilities, which includes verifying the reliability of raw data from various IMU sensors.

In terms of safety, our team is committed to following the laboratory safety regulations set by the Division of Research Safety in the Office of the Vice Chancellor for Research and Innovation (ECE 445 p.3). To minimize any potential risks, our team will work in pairs during laboratory sessions, promptly report any broken equipment, maintain cleanliness after each session, and avoid consuming food within the lab. Additionally, we will exercise caution to avoid skin contact with electrical circuits and separate electrical systems from external irrigation systems that release water over croplands.

6. Citations and References

[1] "NGIMU: The Complete Sensor Fusion Solution." X-IO Technologies, www.x-io.co.uk/ngimu/.

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[3] "IEEE Code of Ethics." IEEE, www.ieee.org/about/corporate/governance/p7-8.html.

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[6] "Adafruit 9-DOF Absolute Orientation IMU Fusion Breakout - BNO055." Adafruit Industries, LLC, www.adafruit.com/product/4502.

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[8] "denoise-imu-gyro." GitHub, github.com/mbrossar/denoise-imu-gyro.