Comparing Filter Efficiency: Complementary vs. Kalman Filters on Accelerometer and Gyroscope Signals

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***Abstract* — This paper explores the application of complementary and Kalman filters in signal filtering obtained from accelerometers and gyroscopes. Accelerometers and gyroscopes are commonly used sensors in various applications such as navigation, aircraft stabilization, robotics, and sports. However, signals obtained from these sensors are often susceptible to noise, vibrations, and other effects that can affect measurement accuracy and result in unreliable data. The complementary filter combines data from both sensors in a way that minimizes errors and provides a stable estimation of the object's orientation in space. On the other hand, the Kalman filter uses mathematical system models and statistical methods to optimize the state estimation of the system based on measurements from both types of sensors. The goal of the research is to compare how effectively signals are filtered using both a simpler and a more sophisticated filter.**

Keywords — MPU6050; MPU 9DOF; accelerometer; gyroscope; signals; complementary filter; Kalman filter

I. INTRODUCTION

Filtering analog signals represents a fundamental step in signal processing that enables the removal of noise, unwanted frequencies, and enhances signal quality. This process finds wide application across various domains including telecommunications, audio processing, medical diagnostics, automation, electronics, and many others.

One of the primary reasons for filtering analog signals is the elimination of noise that may occur during signal acquisition or transmission. Noise can be caused by various factors including electrical interference, electromagnetic radiation, thermal oscillations, and other external influences. Filtering allows for the extraction of useful signals from unwanted noise, thereby improving the accuracy and reliability of measurements.

Interferences may be present in analog signals due to signal mixing with other sources or channels. Eliminating these interferences preserves the purity and integrity of the signal. For example, in radio communications, filters are used to isolate signals from specific radio stations and reduce mutual interference.

In this study, two filters will be applied to signals coming from MPU6050 and MPU 9DOF sensors. The operation of the filters on the pitch angle will be demonstrated, as well as examples of filtering for all angles for three-dimensional orientation in space. The study explores which filter provides better results in filtering signals obtained from accelerometers and gyroscopes.

Researching the difference between complementary and Kalman filters enables a better understanding of their characteristics, advantages, and disadvantages for more efficient application. This may include analyzing signal stability, noise reduction, and improvement in measurement accuracy.

II. ACCELEROMETER, GYROSCOPE AND MAGNETOMETER

Accelerometer is an electromechanical component that measures the forces of acceleration of a moving body [1]. It is used for various purposes, including load indication, measuring distance traveled, aircraft and missile guidance, and more.

There are several different designs of accelerometers. Some accelerometers use the piezoelectric effect - they consist of crystal microstructures that move due to the force of acceleration and generate voltage. Another method is

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detecting changes in capacitance. If we have two microstructures, one next to the other, capacitance occurs between them. If the force of acceleration moves one of the microstructures, the capacitance will change. This change can be detected by an electronic circuit and converted into a voltage change. There are other methods as well, including the piezoresistive effect, the transmission of hot air bubbles, etc.

A gyroscope is a device used for navigation and measuring angular velocity.

Within a mechanical system or device, a conventional gyroscope is a mechanism composed of a rotor designed to rotate about one axis [2]. The rotor carrier is attached to the inner gimbal ring, the inner ring is connected to the outer ring, which is attached to the support ring so that it can rotate about its own axis in a plane determined by the support, as it's shown on the Fig. 1. The outer ring has one degree of rotational freedom. The inner ring is mounted on the outer ring so that it rotates about its own axis in a plane that is always vertical to the axial axis of the outer ring. The rotating axis of the wheel determines the axis of rotation. The inner gimbal ring has two degrees of freedom, and its rotational axis has one. The rotor is attached to rotate about an axis that is always vertical to the axis of the inner ring. Thus, the rotor has three degrees of rotational freedom, and its axes have two. The wheel responds to the force applied around the input axis with a reaction force around the output axis.

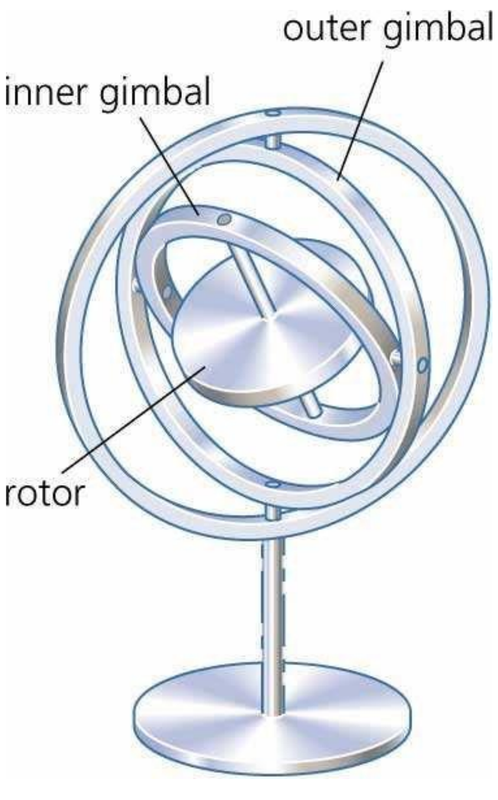

Fig. 1. Gyroscope [3]

A magnetometer is an instrument for measuring the strength of a magnetic field. There are various designs, depending on whether a variable or constant magnetic field is being measured [4].

A magnetometer for measuring the strength of a variable magnetic field (caused by the passage of alternating current) is a coil in which a voltage is induced according to Faraday's law of electromagnetic induction. This is then displayed on an appropriate scale or further processed.

A magnetometer for measuring the strength of a constant or gradually changing magnetic field is of a different construction. For example, let's take the American Mk.6 Mod 0-4 magnetometer. It has two metal cores with oppositely positioned windings through which alternating current of 800 Hz flows. Above the cores is wound a compensating winding powered by a battery.

At zero external magnetic field, the electromagnetic influence of the cores is canceled out, so the indicator is at zero. When the instrument is placed in a magnetic field of a certain direction, the cores saturate, so the current in one winding increases and in the other decreases. This leads to a change in the indicator current, which becomes positive or negative, depending on the direction of the magnetic field. By changing the calibrated current value of the compensating winding, the pointer returns to zero and the field strength is read off by the current required for compensation. The scale is in oersteds or millioersteds.

Fluxgate magnetometers like the Mk.6 Mod 0-4 provide precise measurements of magnetic fields and are valuable tools in various fields such as geophysics, navigation, and military applications. An example of a fluxgate magnetometer is shown in the Fig. 2.

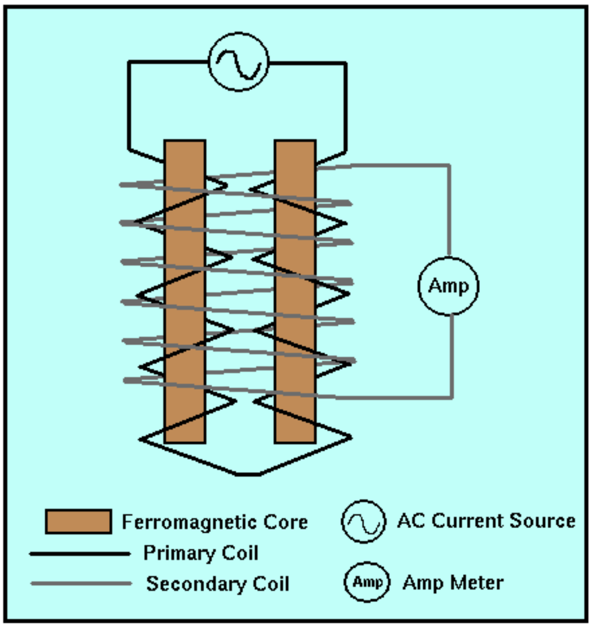

Fig. 2. Fluxgate Magnetometer [5]

III. MPU6050

The MPU6050, shown on Fig. 3, is a six-axis motion tracking device used for determining position and orientation. It combines a 3-axis gyroscope, 3-axis accelerometer, and Digital Motion Processor (DMP) [6]. The DMP relieves the intensive computation demands of motion processing. Essentially, the MPU6050 module's built-in processor combines data from the accelerometer and gyroscope to facilitate more accurate determination of an object's position and orientation. Additionally, the MPU6050 features a

VLOGIC reference pin (alongside the analog pin VDD for logical reference and analog device power) and only supports communication via the I2C serial interface.

This sensor has the capability to connect to a magnetometer, resulting in a 9-axis positional sensor.

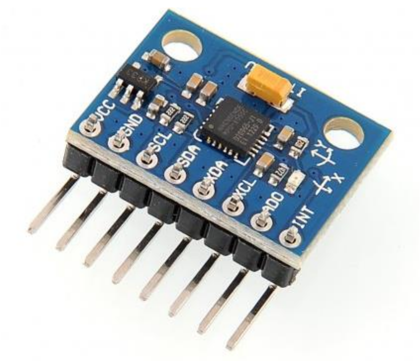

Fig. 3. Sensor MPU6050 [7]

IV. MPU 9DOF (MPU9250)

The MPU9250 is another advanced sensor module that provides a wide range of capabilities for motion tracking and position determination in space. This module combines a 3-axis gyroscope, 3-axis accelerometer, and 3-axis magnetometer, enabling motion tracking in all three axes, resulting in a complete 9-axis system.

The gyroscope provides information about the rotational speed in the three axes, the accelerometer measures acceleration in three directions, while the magnetometer determines orientation relative to Earth's magnetic polarities. The combination of these sensors allows the device to accurately determine position and orientation in three-dimensional space.

The MPU9250 also features a built-in DMP that processes data from the sensors, relieving the main microcontroller and facilitating the implementation of complex motion processing algorithms. It has the same interface capabilities as the MPU6050, including support for communication via I2C [8]. This specific sensor can be seen in the Fig. 4.

By incorporating the magnetometer, the MPU9250 becomes a complete 9-axis position sensor, making it ideal for various applications such as navigation, spatial orientation, virtual reality, and augmented reality.

Fig. 4. Sensor MPU 9DOF [8]

V. Raw Data

When it comes to raw data obtained from accelerometers, gyroscopes, and magnetometers, there may be some common issues during data acquisition and processing.

Raw data can be susceptible to noise, which can be caused by various factors such as electrical signals, mechanical vibrations, or external influences. Additionally, aliasing can occur. This happens when the frequency of the signal exceeds half of the sampling frequency, which can lead to the appearance of false frequencies in the data.

Sometimes, problems can be caused by hardware damage to the sensors or incorrect connections to the microcontroller or other devices. The magnetometer may be susceptible to interference from metallic or magnetic materials nearby, so it is necessary to ensure that there are no such interferences during measurements.

All sensors have certain variations and errors in measurements. Calibration is the process by which these variations are compensated to ensure measurement accuracy. For the accelerometer, this may involve zero point and axis calibration, while for the gyroscope and magnetometer, it may involve calibration to eliminate drift and the influence of magnetic fields.

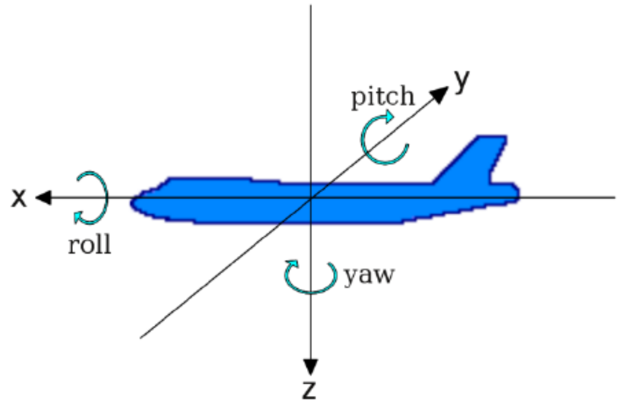

Fig. 5. Pitch, roll and yaw [9]

The fundamental angles used to describe objects in three-dimensional space are pitch, roll, and yaw (Fig. 5.).

Pitch is the angle that describes rotation around the lateral axis of the object. Pitch measures the forward or backward tilt of the object relative to the horizontal plane. When the object tilts forward, the pitch will be positive, and when it tilts backward, the pitch will be negative.

Roll is the angle that describes rotation around the longitudinal axis of the object. Roll measures the left or right tilt of the object relative to the horizontal plane. When the object tilts to the right, the roll will be positive, and when it tilts to the left, the roll will be negative.

Yaw is the angle that describes rotation around the vertical axis of the object. It measures the rotation of the object around the vertical axis and describes its orientation in the horizontal plane. It determines the direction in which the object is facing, with the angle measured relative to the reference point (usually the north direction).

The combination of these angles allows for a complete three-dimensional orientation and rotation of the object.

Due to the lack of a magnetometer on the MPU6050 sensor, only the influence of the accelerometer and gyroscope will be considered. However, using only the accelerometer and gyroscope to determine the yaw angle can result in errors and instabilities, especially in the absence of a magnetometer and other influences. The gyroscope can have significant drift, meaning it will become inaccurate over time. This can cause gradual drifting of the yaw angle even when the object is not rotating.

For this reason, the yaw angle will be neglected, and only the pitch and roll angles will be observed.

Fig. 6. shows the values of the accelerometer (AccelX) and gyroscope (GyroX) obtained by rotating the sensor around the x-axis, that is, rotating around the lateral axis of the object. This graph allows for the analysis of the rotational dynamics of the object around its lateral axis.

The accelerometer values (AccelX) represent the acceleration in the x-axis direction, while the gyroscope values (GyroX) represent the rate of rotation around the same axis. The combination of these two data allows for a detailed analysis of the rotational motion of the object, such as changes in orientation, rotation rate, and rotational stability.

The values up to the second indicate gradual rotation of the sensor around the lateral axis. After that movement, there is a pause, meaning the sensor is stationary for one second. Following the gradual rotation of the sensor, there is a frequent signal of smaller values, representing faster movement of the sensor with a smaller angle of rotation. After the sixth second, the signal is achieved with slower rotations and greater sensor displacement.

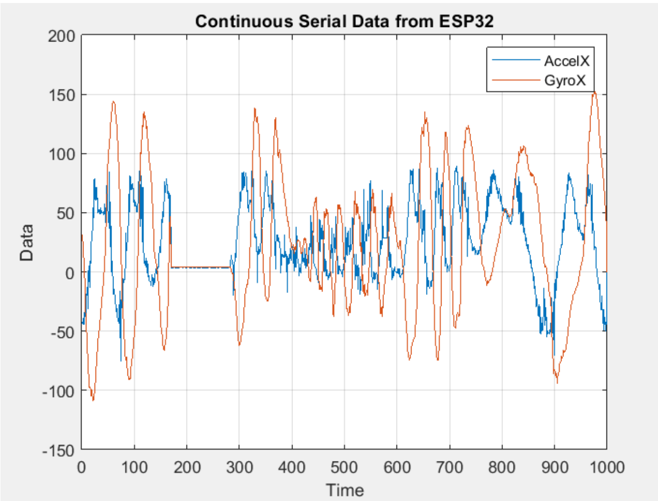

Fig. 6. Raw data values along the x-axis from the accelerometer and gyroscope on the MPU6050 sensor

VI. Complementary Filter

The complementary filter is an algorithm used to combine data from different sensors or sources to obtain a more accurate result. This filter is particularly useful in navigation systems and other applications where sensors such as accelerometers, gyroscopes, and magnetometers are used to determine the orientation of an object in space.

The idea is to take the best characteristics of sensors by measuring the angle using a combination of these sensors (sensor fusion) [10].

What needs to be done is to apply a low-pass filter (LPF) to the angle calculated using the accelerometer to remove possible disturbances, and a high-pass filter (HPF) to the angle measured using the gyroscope to eliminate zero drift. The complementary filter combines these data in a way that minimizes errors and provides stable and accurate orientation.

The accuracy and performance of the complementary filter depend on the proper adjustment of parameters and sensor calibration, as well as the algorithm used to combine data. This filter is widely used in various applications, from stabilizing aircraft and autonomous vehicles to virtual reality and wearable devices.

The results of implementing the complementary filter on the pitch and roll angles for the MPU6050 and MPU 9DOF sensors can be seen in Fig. 7. and Fig. 8. At the beginning of both graphs, the signals are at zero (or very close to zero) because the sensor is stationary. Shortly thereafter, a few random rotations of the sensor were made, followed by a short pause to bring the sensor back to a stationary state. From the fourth second on the graph in Fig. 7. rotations around the pitch axis can be observed, followed by rotations around the roll axis. Since it is not possible to perform a perfect rotation around only one axis, during rotation around the pitch axis, slight displacement of the sensor around the roll axis can be noticed, and vice versa.

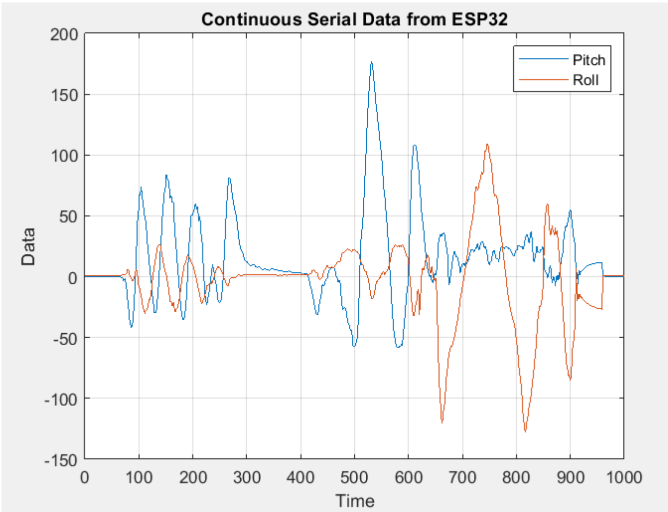

Fig. 7. Complementary filter on the MPU6050 sensor

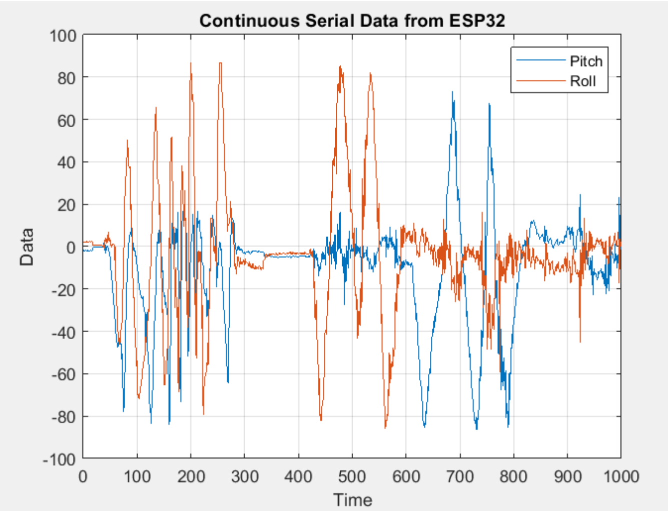

Fig. 8. Complementary filter on the MPU 9DOF sensor

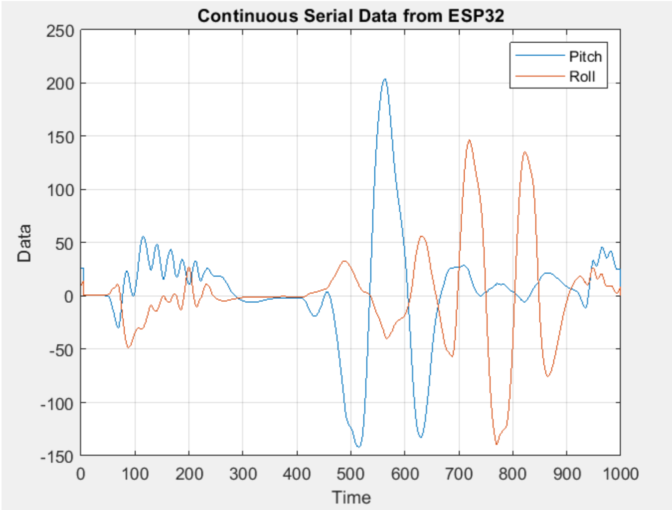

Fig. 9. Kalman filter on the MPU6050 sensor

VII. KALMAN FILTER

The simplicity of the complementary filter leads to a compromise between a well-filtered signal with significant delay and attenuated amplitude, or a signal with minimal delay, good tracking of the actual signal amplitude, but with considerable noise. As an upgrade to this, the Kalman filter comes into play.

The Kalman filter represents a way to predict the next value, knowing the system model on which we measure the data, or based on knowing the model of signal change [10]. This process is repeated iteratively, using mathematical system models and statistical methods to minimize the error between the actual system state and the estimated state.

The results of implementing the Kalman filter on the pitch and roll angles for the MPU6050 and MPU 9DOF sensors can be seen in Fig. 9. and Fig. 10. Here, we can see that the Kalman filter was tested in a similar way to the complementary filter. First, the sensor was placed in a stationary position, and then a few random rotations were made around both axes. When the sensor settles down, it can be observed that it takes a little more time for the signals to stabilize. Additionally, when sudden changes in sensor movement occur, unlike the signals on the complementary filter graphs, the Kalman filter does not produce "spiky" peaks in the signal. We have smooth transitions and a well-drawn signal due to the ability to predict the next sensor movement based on previously read values from the sensor using the Kalman filter.

The signals of gradual rotation of the sensor around individual axes are clear and do not have sudden changes in values or noise.

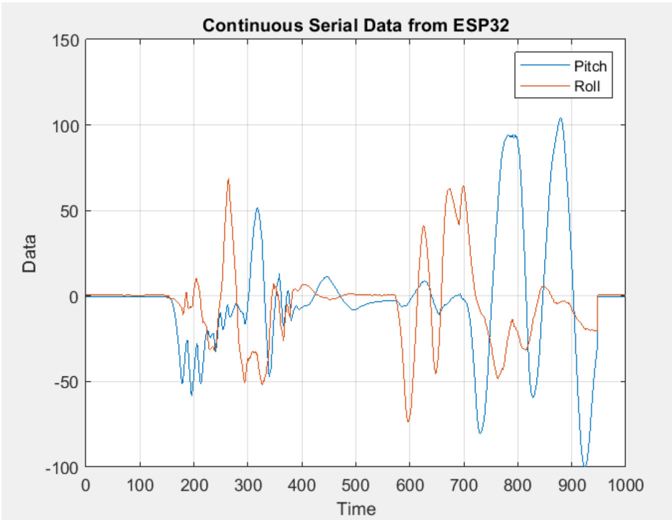

Fig. 10. Kalman filter on the MPU 9DOF sensor

VIII. RESULTS

To observe the difference between the two filtered signals, only the pitch angle on both sensors will be considered. Fig. 11. and Fig. 12. show graphs displaying the signals PitchCompl (pitch angle with the complementary filter) and PitchKalm (pitch angle with the Kalman filter).

The signals from the MPU6050 sensors are stationary at the beginning (the sensor is at rest). When there is a change in position, the complementary filter processes the data first and displays a certain change. The Kalman filter "lags" in processing the data because its task is to predict the next state of the sensor based on previous readings. For this reason, rapid changes in position are better registered with the complementary filter, while the Kalman filter does not catch up to process such changes. However, in certain situations, the Kalman filter processes the signal better and manages to "smooth out" unforeseen jerks or noise that occurs when the sensor moves, which is noticeable on the complementary filter.

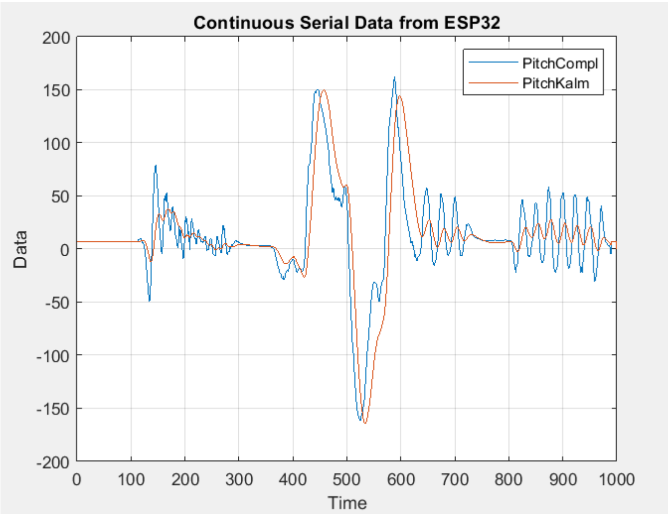

Fig. 11. Pitch angle on the MPU6050 sensor

When testing the MPU 9DOF sensor, the sensor is also initially stationary. Based on the graph in Fig. 12. it is noticed that the complementary signal has more noise and is significantly less stable. Additionally, the "delay" of the Kalman filter is still present, which is quite noticeable in the fifth second when the sensor returns to a stationary state. The complementary filter immediately processed and "calmed down" the signal, while it took about 500 ms for the Kalman filter to stabilize.

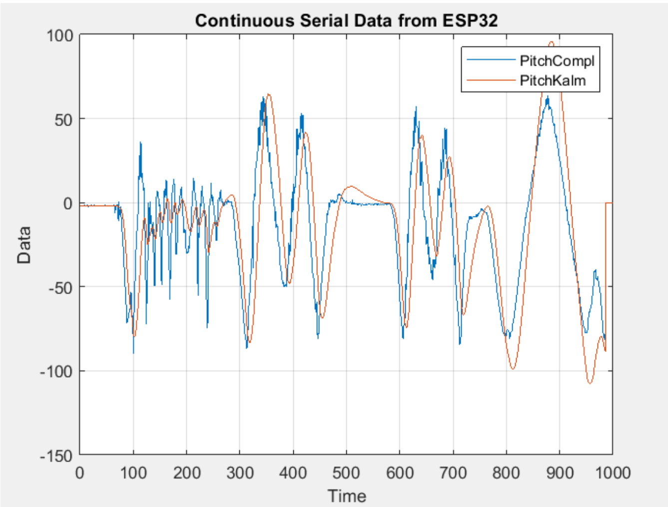

Fig. 12. Pitch angle on the MPU 9DOF sensor

IX. Conclusion

Based on the two graphs in Fig. 11. and Fig. 12. we can conclude that the Kalman filter is a better choice compared to the complementary filter. When comparing, we see that the amplitude decay is significantly less, and the signal is free of noise with the Kalman filter.

Although the Kalman filter has an advantage in better filtering of the signal, it should be noted that it requires precise system modeling to provide the best results. System modeling can be a complex process, especially for non-stationary or poorly understood systems.

During the signal analysis, significant changes in amplitude and exceeding of expected values were observed. This occurs due to deficiencies in signal filtering, that is, imperfections of the filters themselves. It is possible, to some extent, to control these values by changing the coefficients used in the filters as well as changing the signal sampling frequency.

In conclusion, the complementary filter will typically produce a smoother signal with fewer oscillations, while the Kalman filter will provide a more precise and stable signal, with less noise and errors. The choice of filter depends on the specific requirements of the application, its purpose, and the level of accuracy required.

TABLE I
COMPARISON OF ADVANTAGES

Complementary filter	Kalman filter
Simplicity	Handling unreliable measurements
Speed of computation	Adaptability to system changes
Stable and reliable in real-world conditions	Ability to predict future system states
	Adaptability to complex dynamic models

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