Hand Tremor Sensing and Characterisation Device

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by Jackie Le
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1 Abstract

Parkinson’s Disease and Essential Tremor are two of the most common tremor-related conditions affecting millions of people globally. Various types of tremors, specifically in the hand, arise as symptoms characteristic to these tremor-related conditions. However, the lack of standardization and certainty between clinical tremor assessments motivates the future of medical devices to provide relevant medical diagnostics. Current literature shows promise for the ability of such devices to revolutionize home healthcare and integrate well into currently existing clinical procedures. This engineering design project aims to design a wearable medical device to detect and computationally characterise various types of tremors in Parkinson’s Disease and Essential Tremor according to their severity. In the process of doing so, a hand phantom is designed to simulate tremor severities on a set of defined parameters, while real datasets are gathered to provide validation. MATLAB code is run on an embedded system setup to analyse these tremor signals via standard digital signal processing techniques. Tremors were successfully simulated on the hand apparatus, while the live-tracking script was able to record and analyse tremor signals. Improving the accuracy of the classification portion requires further feature extraction and pipeline development, however this project has demonstrated feasibility in the design of an affordable and potentially reliable tremor sensing medical device.
2 Acknowledgment

The guidance of Maggie Delano, Allan Moser, and Joseph Towles made this engineering project possible.

The work accomplished by this engineering endeavor could not have been possible without the guidance of Maggie Delano, Allan Moser, and Joseph Towles, engineering professors at Swarthmore College who have provided expertise in embedded systems, signal processing, and mechanics as it relates to this project. In addition, the support of Ed Jaoudi, J. Johnson, Cassy Burnett, and Josh Jordan ensured that the logistics of this project could be carried out. Last but not least, I would like to thank Peter Jombik, whose willingness to assist with this project and provide relevant data made this endeavor realizable. Thank you all!
3 Introduction

3.1 Parkinson’s Disease & Essential Tremor overview

Tremors describe the rhythmic motion in a person’s body, most commonly occurring in the hand and as a result of various tremor-related conditions[7].

Lewy bodies are particular protein inclusions, which characterize Parkinson’s Disease (PD), the most pervasive neurodegenerative condition with an estimated 8.5 million global cases as of 2019[2]. Lewy bodies induce neural atrophy by disrupting regular neural processes, often beginning from the brain’s substantia nigra region responsible for both dopamine production and movement[14]. Over time, physical symptoms arise, such as hand tremors and abnormal gait.

Essential Tremor (ET) is an overlapping neurological condition primarily marked by tremors, estimated at 400 million cases globally, and 10 times that of PD[3].

3.2 Tremor scales

Clinical assessments outline sets of qualitative measures for evaluating the likelihood of subjects presenting a condition of concern. Evaluations, as highlighted in Table 1, outline key assessments for diagnosing tremor-related conditions, such as PD and ET.

<table>
<thead>
<tr>
<th>Tremor scale</th>
<th>Primary use case</th>
<th>Assessment description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fahn-Tolosa-Marin Tremor Rating Scale (FTM)</td>
<td>Any tremor-related</td>
<td>Versatile and detailed</td>
</tr>
<tr>
<td>Essential Tremor Rating Assessment Scale (TETRAS)</td>
<td>Essential Tremor</td>
<td>Specific to ET, short and simple, displacement-focused</td>
</tr>
<tr>
<td>Unified Parkinson’s Disease Rating Scale (UPDRS)</td>
<td>Parkinson’s Disease</td>
<td>Specific to PD, long and detailed, behavioral and displacement</td>
</tr>
</tbody>
</table>

Table 1: Tremor scales comparison
The Fahn-Tolosa-Marin Tremor Rating Scale (FTM), created in 1988, set a precedent for tremor classification, and has been a versatile method for measuring whole-body tremor severity with a detailed variety of tasks, such as handwriting, eating, and speaking. Ratings by both the examiner and subjects provide an inclusive scale that has been recommended by the official Movement Disorder Society (MDS) for reliability and validity.

The Essential Tremor Rating Assessment Scale (TETRAS) targets ET via a short and simple array of assessments dependent on precision tasks, such as handwriting, standing, and object-oriented actions. These tasks measure displacement amplitudes at differing extremities, particularly at the upper limb, and is additionally a recommended scale by the MDS for its use case.

The Unified Parkinson’s Disease Rating Scale (UPDRS), as revised by the MDS, classifies PD by considering both psychological and physical aspects of prone subjects. Because PD varies greatly by case, this scale encompasses measures ranging from cognitive impairments and emotional well-being to capabilities in daily living.

The FTM, TETRAS, and UPDRS scales each offer reliable qualitative diagnostics for tremor-related conditions. However, these ratings depend on subjectivity of examiners, which produces uncertainty in assessment results. As critiques from the Movement Disorder Society mention, examiner ratings are subjective for these aforementioned scales, and training is often needed to obtain a high measure of inter-rater reliability, which even to the trained eye may falter when making observations of sensitive motions in the hand. As a result, examiners require initial training, which may pose implementation issues for healthcare in underresourced communities. The lack of accurate diagnoses can be the difference between access to critical treatment and improper care. As just one example, people living with PD may qualify for a Deep Brain Stimulation (DBS) treatment, by which a neurostimulator is implanted into the body for the corresponding device to produce pulses that disrupt the signal that cause tremors. Qualifying for this surgical procedure requires patients to be experiencing uncontrollable symptoms not able to be controlled by current medication, which clinicians would have assessed and provided.

These concerns motivate the use of quantifiable measures to improve currently existing clinical methods. In doing so, hand tremors become a key point of investigation for numerous reasons, as enumerated below.
3.3 Hand tremor motivation

Hand tremor attributes lend well to medical diagnostics because they can be noninvasively measured, thus enabling seamless collection of biophysical data. This measure shows predictive potential because of their being hallmark characteristics of 70% of cases presenting PD, as well as ET in its entirety. This attribute defines subcategories within the FTM, TETRAS, and UPDRS scales, which affirms their significance in diagnosis. Additionally, implementing such tracking has been shown to be well-integrated into the home healthcare ecosystem and existing clinical tremor assessment procedures, making improvements to existing diagnostics highly feasible.

3.4 Hand tremor definition

Hand tremors are characterized by a rhythmic nature, which can be exhaustively categorized as below in Figure 1.

The broader picture divides tremors into what are rest and action. The rest tremor is defined by the absence of voluntary muscle contraction, wherein the force of gravity completely supports the extremity\(^8\). An elementary example imagines a seated person whose hand settles on their lap. Meanwhile, the action tremor captures a broad set of tremors in which muscle contraction occurs, known as postural and kinetic tremors. The kinetic tremor highlight objective-oriented actions, while postural tremor subtly differs in that it captures actions that simply opposed the force of gravity, such as lifting an arm. It is important to note that additional nuances exist to further classify tremor activation patterns, which assist in characterizing associated and overlapping conditions.

The global prevalence of PD and ET gives rise to their study. In particular, there exists two primary tremor motions that differentiate the two, as highlighted in Table 2.

<table>
<thead>
<tr>
<th>Hand tremor types</th>
<th>Rest tremor</th>
<th>Action tremor</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Tremor foci</strong></td>
<td>Pill-rolling tremor</td>
<td>Postural tremor</td>
</tr>
<tr>
<td><strong>Associated condition</strong></td>
<td>Parkinson’s disease</td>
<td>Essential tremor</td>
</tr>
</tbody>
</table>

Table 2: Tremor types, specifically for PD and ET

Pill-rolling tremor defines the thumb’s movement as it traverses along
the index finger, as if a pill were lodged between the two digits. This motion occurs most exclusively in cases of PD, making it an obvious choice for quantification. On the other hand, postural tremors typically define ET more intensely. Coincidentally, each type of tremor motion is separated by their broader tremor type, which could assist in differentiation of the two rhythms.

To explore tremor characterisation and potential differential diagnosis, a computational approach is taken to identify the underlying pattern of hand tremors, whose mathematical nature lends itself to analytical tools that will be discussed in the subsequent sections.
4 Theory

Hand tremors can be identified by a mixture of features in layman’s terms, from which a mapping can be drawn to translate these elements mathematically, as in Table 3.

<table>
<thead>
<tr>
<th>Hand tremor element</th>
<th>Mathematical description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spatial location</td>
<td>Spatial position</td>
</tr>
<tr>
<td>Regularity</td>
<td>Frequency</td>
</tr>
<tr>
<td>Spatial direction</td>
<td>Vector velocity</td>
</tr>
<tr>
<td>Intensity</td>
<td>Amplitude</td>
</tr>
<tr>
<td>Event cue</td>
<td>Classification</td>
</tr>
<tr>
<td>Time progression</td>
<td>Time dynamics</td>
</tr>
</tbody>
</table>

Table 3: Mathematical translation of hand tremor elements

In this light, concepts from signal processing, mechanics, and embedded systems are taken to account for these hand tremor elements.

4.1 Signal processing

The Fourier Transform is commonly used to analyze time-series data in the frequency, as defined by Equation 1.

\[
X(k) = \sum_{n=0}^{N-1} f(n)e^{-j2\pi kn/N} \tag{1}
\]

This transform separates a signal into frequency components, producing a frequency spectrum that identifies peaks at which particular frequencies are dominating. Hand tremors are oscillatory by nature, and when realistically measuring the tremor motion, only discrete values are taken. Hence, implementation of frequency analysis uses the Discrete Fourier Transform, which applies a summation rather than integral for continuous and infinite values. This discrete-form implementation comes as a result of hardware capabilities, which sample at finite values. This becomes important when paying attention to finer scales, at which discontinuities are more obvious.
4.2 Embedded system

An inertial measurement unit (IMU) is considered as a means to record tremor motion in real time, which works by tracking the microdisplacement of a delicate mechanical structure in relation to its orientation against the force of gravity. The precision of these measurements are a result of the combined degrees of freedom (DOF) enabled by the Piezoelectric effect, Coriolis effect, and electromagnetism, which all help to measure the change in small displacements as a voltage, enabling highly sensitive and precise measurements. Figure 2 highlights the electromechanical aspect of the IMU sensor.

![Mechanisms of IMU with 9 DOF](image)

Figure 2: Mechanisms of IMU with 9 DOF

Part of tracking these measurements is the sampling frequency, for which the Nyquist criteria, as shown in Figure 3, forms a basis for full signal data capture. Nyquist’s theorem says that the sampling rate of a hardware must be at least twice that of the maximum frequency of interest.

The IMU collects data in terms of acceleration as the sensor moves with a system, in this case the hand apparatus. Before any recording may take place,
an appropriate system must be designed, in which we enter the mechanics side of the project.

![Diagram](frequencyNyquistDiagram.png)

**Source:** Singh *et al.* (2018)

Figure 3: Chart details of Nyquist criterion

### 4.3 Mechanics

Hand tremors can be approximated by their yaw, pitch, and roll, terms for rotational motion about the $x$, $y$, and $z$ axes typically used to describe aviation.

The same rotational principles can be mapped to the hand, as in Figure 5, and in this way, the DOF can be defined according to yaw, pitch, and roll, such that primary tremor motions can be captured by these degrees. The postural tremor, mainly characteristic of ET, is approximated by one DOF, the wrist roll. Meanwhile, the pill-rolling tremor, characteristics of PD, takes a step up and is approximated by two DOFs: primarily the wrist roll and thumb pitch.
Figure 4: Yaw, pitch, roll orientations for a plane

Figure 5: Yaw, pitch, roll orientations for a hand
5 Methods

The ultimate aim of this project is to design a wearable medical device to characterize tremors in PD and ET. In this process, the device captures and computes tremor features, such as frequency and amplitude to be able to classify overall tremor severity. Because of the ethical considerations that testing the device for feedback will require, a hand apparatus phantom will be designed and utilized as a substitute for simulating tremors, which will have parameters to adjust tremor severity. Experimental design for this project is defined by the design considerations, which are elaborated on below.

5.1 Design considerations

Constraints that govern the design of this project is the budget and timeline of the project, for which $400 have been allocated for this Swarthmore spring semester 2024. Tremor motion must be quantified with measurements for either acceleration, velocity, or displacement, hence an IMU must be used. Because the maximum frequency that could be captured from either PD or ET tremors would fall within 12 Hz, by the Nyquist theorem the IMU must achieve a sampling frequency of at least 24 Hz to capture the maximum possible range typical for PD and ET tremors. In order to additionally capture a representative sample for characterizing hand tremors for a particular subject, the wearable device must be able to take at least 30 seconds of prolonged measurements. To minimize user fatigue, the wearable device must fall within 35 grams in weight, comparable to existing daily wearables (e.g. smartwatches). To properly analyze and track the tremor data, the medical embedded system must additionally be able to transmit data to a computer interface, where a combination of the MATLAB and Arduino programming languages will be used to break down sample tremor data.

In the process of fulfilling these constraints, the medical device must satisfy a set of design requirements. By following a classification pipeline, the script must be able to control for drift inherent to the tremor data being collected by an accelerometer, doing so by using signal processing techniques. Additionally, the scripts must be capable of classifying the tremors on a severity index of 1-5, in line with the FTM, TETRAS, and UPDRS scales described above. Simulating the hand tremors requires the design of a hand apparatus phantom, which must be capable of capturing prime tremor motions in both pill-rolling and postural tremors. In order to capture tremors
effectively, the phantom must also include a stochastic element.

Evaluating the constraint and design requirements is twofold. In regards to the hand apparatus phantom, it is to be assessed by its accuracy in replicating tremor types. Validating this performance will include a mix of comparison to videos of actual hand tremors, and the phantom’s capabilities to achieve desired frequencies and amplitudes as defined in the tremor scales and online literature. Meanwhile, the IMU and code will be evaluated by its ability to detect different amplitudes and frequencies. This will be compared to ground truths established by hard-coded parameters driving the hand phantom.

The focus and niche of this project meant that no professional standards and codes for medical device regulations existed to be followed accordingly, as no regulation precedent exists for this kind of device. However, various points of concern must be addressed for this project to proceed safely and effectively. For one, soldering is required to create the device, which places importance on building clear circuit paths for electricity to flow, especially in consideration of the user. Electricity transfer between the device and skin may occur, however given the device may be attached to an Arduino, the safety depends on the current and voltage that may be generated from the system, which is likely to be low given the small scale IMU sensor.

5.2 Hand apparatus, embedded system, code setup

The hand apparatus is designed to accommodate for two degrees of freedom, the roll and pitch. Anatomically, the wrist is a pivot that enables roll, while the pivot of the thumb enables pitch. To a first approximation, the hand can be treated as an assembly of wooden blocks that pivot around these DOF, one block for the entire palm of a flat hand, and another block exclusively for the thumb.

Two servo motors, the TowerPro MG92B and Multi-Mode Smart Servo 200, installed at these DOF positions are connected by an ArduinoUNO Rev3 Microcontroller Unit (MCU), which is attached at the backside of the phantom. A breadboard placed on the frontside of the phantom equally transmits the 5V power and ground channels to both of these motors, in addition to an IMU sensor. The sensor has two locations for potential measurements: one where index finger would be (1 DOF), and another on the thumbtip (2 DOF). Both locations will be used to explore tremor motion mathematically.

The script designed in the ArduinoIDE is used to oscillate the two servo
motors between separate initial and final angles. Increasing this sweep also increases the tremor severity because the amplitude grows. Decreasing this sweep has an inverse effect. Additionally, the script executes via a non-blocking approach to simultaneously allow the IMU to sample. The IMU operates at a baud rate of 115200 and sampling frequency of 200 Hz.

The MATLAB script transcribes the live IMU tracking, and provides additional tremor analysis, including live plots, denoising techniques, and spectral analysis via the fast version of Fourier Transform. The details of this routine are in Figure 10.

Methods were applied to both real and simulated tremor data. The simulated data came from the trial runs produced by the hand apparatus. The real datasets came from Peter Jombik, a researcher whose similar interests in tremor characterisation were used as a way to establish both a ground truth and simultaneously develop a working signal processing routine. Both data file formats are shown in Figures 8 and 9.
Figure 7: Simulated tremor signal data, with columns (Yaw, Pitch, Roll, X”, Y”, Z”)

Figure 8: Real tremor signal data, with columns (X”, Y”, Z”, EMG)

Each tremor signal file is run through the signal processing routine denoted in Figure 11. In this process of praising and cleaning the data in the frequency domain, it is converted from the originally collected acceleration values to displacement in order to be implemented with the tremor scales. The primary focus of this application is a segment in both the UPDRS and TETRAS scales that highlight the hand tremor amplitude as being measured by their maximum displacement at any point during the examination period. As a result, a huge emphasis is placed on the scaling of these tremor signals as these computations are being implemented. Figure 9 highlights these specific assessment categories.
Figure 9: Hand tremor assessment categories of both UPDRS and TETRAS scales, respectively.

![Hand tremor assessment categories table]

**Figure 10: Tremor signal processing routine**
6 Results & Discussion

The multiangle approach of this project comes as result of both the clinical motivation and environmental constraints. As mentioned before, the hand apparatus was designed to simulate tremors, in lieu of having people living with PD and ET tremors to collect tremor data from. Consequently, real data is analysed to define a partial ground truth with which to based results from simulated data with. One primary measure is characteristic frequencies of PD rest tremors and ET rest tremors, which are elaborated on below.

6.1 Data analysis

Analysis is performed with hand tremor data from people living with PD and ET, for a total of 12 .txt files each sampled for 60 seconds at 200 hertz. One file instance, as it passes through a signal processing routine, is covered in detail to elaborate on the pipeline for tremor characterisation. This begins with a time-series plot of raw acceleration collected from an IMU sensor, in Figure 12.

![Figure 11: Raw time-series tremor acceleration in Euclidean space of PD rest tremor](image)

Plots in each Cartesian coordinate exhibits two-order, nonlinear, and no-strictly periodic oscillation[5], with a mixture of both stochastic and deterministic elements. Parkinsonism is clear when observed in the frequency
domain. Figure 13 reveals dominant frequencies between 4 and 6 hertz, characteristic of Parkisonian rest tremor [13].

Figure 12: Frequency spectrum of raw tremor acceleration in Euclidean space for PD rest tremor

Discrete conversion from acceleration to velocity then displacement obeys Newtonian principles relating the three quantities. Figures 14 and 15 respectively showcase each result as time-series plots.

Summing from a second-order theoretically maintains oscillatory behavior for a first-order. However, summing again appears to entirely change the time-series dynamics.

This effect could be a result of drift captured by a gravitational force involved in each summation operation. For static acceleration, direct conversion to displacement gathers a $9.81 \ m/s^2$ term as a function of time squared, which by its second-degree polynomial produces parabolic characteristic observed in Figure 14.

However, a direct summation also maintains the pure tremor elements from velocity and acceleration. Finer scales reveal these oscillatory patterns as before. This squiggle observation may be also be explained by numerical rounding errors introduced by operations, however the precision of this floating point representation and that required for simple, direct summations is not a concern.

This accelerative drift is not present in frequency spectrum plots of previous time-series acceleration, but is observed in that for velocity, which by applying the fft() function in MATLAB generates Figure 16.
To remove this drift, MATLAB’s filterDesigner toolbox was used to design a high-pass filter, specifically as an FIR equiripple filter to minimize ripple and, therefore, preserve tremor motion. Table 4 elaborates on the filter parameters.

<table>
<thead>
<tr>
<th>Filter parameter</th>
<th>Description</th>
<th>Value</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>$F_s$</td>
<td>Sampling frequency</td>
<td>200</td>
<td>Hertz</td>
</tr>
<tr>
<td>$F_{stop}$</td>
<td>Stopband frequency</td>
<td>0.1</td>
<td>Hertz</td>
</tr>
<tr>
<td>$F_{pass}$</td>
<td>Passband frequency</td>
<td>0.3</td>
<td>Hertz</td>
</tr>
<tr>
<td>$A_{stop}$</td>
<td>Stopband attenuation</td>
<td>60</td>
<td>Decibels</td>
</tr>
<tr>
<td>$A_{pass}$</td>
<td>Passband ripple</td>
<td>0.3</td>
<td>Decibels</td>
</tr>
</tbody>
</table>

Table 4: High-pass filter parameter specifications

Digitally, convolving both the high-pass filter and tremor velocity signal removes the drift. Converting to displacement and computing the Euclidean norm of the filtered displacement in each direction yields Figure 17.

Transient artifacts are observed on both time interval endpoints, a potential effect of non-ideal filter design. However, the 1 centimeter maximum amplitude displacement observed at approximately $t = 27$ seconds falls into a mild tremor severity value at the cusp of 1 and 2, according to the UPDRS. Clinical studies performed on $n = 197$ subjects with Parkinsonian tremor
Figure 14: Raw time-series tremor displacement in Euclidean space of PD rest tremor yielded an average UPDRS score of 1.04 for rest tremor [10]. This result, albeit with analysis of one tremor signal, holds promise for characterisation and classification of various tremors.

This entire process can be applied similarly to ET data. Figure 15 reveals a dominant peak frequency between 4 and 12 hertz, characteristic of ET postural tremor [12]. ET postural tremors typically experience higher dominant frequencies.

Plotting the ET velocity waveforms convolved with a high-pass filter of the same parameter set yields Figure 18.

According to this plot, the maximum amplitude displacement is well below 1 centimeter, which does not classify it as the lowest possible score on the TETRAS. This observation is noted across the numerous Essential Tremor files, which may beg further computational investigation to determine validity.

Simulated data from the hand apparatus successfully captured two DOFs for approximating the pill-rolling tremor characteristic of PD rest tremors. Figure 17 showcases a plot of the acceleration data measured by the IMU sensor, which exhibits high sensitivity and fluctuations over time. The angle parameters chosen for the wrist roll and thumb pitch during this trial was respectively $\theta_{\text{wrist}}$ between 25 to 65 degrees and $\theta_{\text{thumb}}$ between 105 to 150 degrees. These sweep angles were experimentally determined to qualitatively capture hand tremors.
Figure 15: Frequency spectrum of tremor velocity for PD rest tremor

Despite this observation, it is unclear whether or not the previously applied signal processing routine in MATLAB would successfully classify these simulated tremor motions. In doing so, the accuracy and implementation of such IMU sensors would be evaluated to determine whether such a wearable device could be effective in comparison to existing expensive clinical interventions.
Figure 16: Frequency spectrum of magnitude of filtered tremor displacement for PD rest tremor.

Figure 17: Frequency spectrum of raw tremor acceleration in Euclidean space for ET postural tremor.
Figure 18: Frequency spectrum of magnitude of filtered tremor displacement for ET postural tremor

Figure 19: Simulated pill-rolling tremor acceleration data plotted in 3D
6.2 Conclusion

Ultimately, the objectives set out by this project were explored thoroughly, while prompting further questions that more research would be able to address. For one, the hand apparatus was able to successfully oscillate between two DOFs to approximate both the PD pill-rolling and ET postural tremors. The basic criteria for this objective was to obtain a deterministic yet slightly stochastic system to simulate these tremor motions. In addition, the wearable embedded system was able to successfully track through a tremor motion for a predetermined amount of time, in this case 30 seconds. Doing so enables future steps to be taken towards collecting data from the hand apparatus. In terms of the signal processing, a MATLAB script was developed to successfully parse, clean, and analyse real tremor data. Future research would apply this script to simulated tremor data, which would tie together the setup done on all the embedded system, hand apparatus, and signal processing aspects of this engineering endeavor.

At the same time, numerous assumptions were placed to enable the pursuit of this project. Primarily, tremors could be approximated with a hand apparatus and 2 DOF. This implementation mainly depended on qualitative observations of PD and ET tremors, and thus a more quantitatively-backed measure for determining the accuracy of this approximation, alongside a modeling simulation would improve the design and simulation output. Furthermore, in removing drift from the acceleration data, the accelerometer data was largely assumed to be static. Hence, applying a high-pass filter could be reasonably set to constant parameters and classification results were promising. However, realistically this is not the case, and dynamic acceleration plays a significant role in the drift that occurs in displacement, as a function of the orientation of the sensor. Literature not only describes the rounding error that it may take to precisely convert this acceleration to displacement, but also the computational complexity to account for the changing force of gravity as this accelerometer moves in space[9].

But ultimately, this more controlled environment for simulating hand tremors is beneficial because it helps to further confirm whether hand tremors have an inherent and analysable patterns, an objective that would be difficult to isolate in the clinical setting. In addition, the long-term future of this project would consider how the user actually interfaces with the wearable device, which would involve gathering user feedback.
References


7 Appendices

7.1 Arduino code

Refer to the following GitHub profile for access to repositories for the Arduino code implemented for this project.

https://github.com/poetle

7.2 MATLAB code

Same as the Arduino code subsection right above, refer to the following GitHub profile for access to repositories for the MATLAB code implemented for this project.

7.3 Filter designer

Figure 1: Diagram of filter design parameters
7.4 Hand apparatus setup photo angles

Figure 2: Bottom view of hand apparatus, showcasing Arduino board

Figure 3: Thumb view of hand apparatus, showcasing IMU sensor placement
Figure 4: Top view of hand apparatus, showcasing breadboard connections