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Seismic Event Detection using MEMS Accelerometers

Semester Thesis

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Abstract

Physical sensors have been used to measure seismic signals to understand structures and processes on our planet for hundreds of years [1]. As technology has evolved, these sensors have improved in quality and have become more specifically designed for the individual fields of operation. As the alpine permafrost melts [2, 3], new methods are needed to monitor and predict these changes in order to estimate the risk of catastrophic and sudden destabilisations, like mudslides in the alps.[4]
The idea to use microelectromechanical systems (MEMS) sensors for seismic sensing has already been brought up a decade ago, but was seen as not technologically mature enough at the time. [5]. Ten years have passed, and a lot of technological progress has been made in MEMS sensors since. In this thesis, we want to analyse the feasibility of these types of sensors, particulary MEMS accelerometers, for seismic sensing.
We analyze the utility of various types of MEMS sensors for our application, create a test platform for a modern ultra-low power MEMS accelerometer, and assess its performance.
We demonstrate a high potential of MEMS accelerometers for this application with sensitivity depending heavily on sampling rate.
The type of tested accelerometer is already deployed in the field in an existing geophone sensor platform. The findings of this thesis and the developed operation modes will be used to better utilize those sensors and give additional insights on the feasibility of a stand-alone MEMS sensor platform.

Contents

Chapter 1

Introduction

The detection of seismic events has been of importance for nearly two millenia: The first known example of such a device was developed in 132 AD in ancient China [1]. Understanding the processes under the soil we walk on has sometimes been just a fascinating topic to think about, other times it has been essential in order to estimate where we can build our houses without losing them a couple years later, or where we can travel safely.
The latter has in recent years become a hot topic again in mountainous regions, especially in the alps. Processes like the thawing of permafrost or the destabilisation of rock glaciers is believed to lead to an increase in catastrophic mudslides, an example of which can be seen in Figure 1.1.
As many inhabited and touristically used alpine regions have come under an increasing threat of worsening instabilities of mountains, their monitoring has become increasingly important. In this thesis, we investigate whether the advances in MEMS sensors enable us to create a dense distributed sensor network in high-risk areas.

Figure 1.1: The mudslide in Bondo.

1.1 Seismic Sensing

A wide range of sensors have been and continue to be used to measure the movement of the earth, to study the structure and movement of the earths crust. One application is the measurement of earthquakes, another one is to measure the activity of mountains. An overview of various seismic signals and different sensing technologies will be given in Chapter 2.

1.2 Motivation

These activities take place in large and remote areas, so the used sensors have unusual requirements: Small size, cost and energy requirements as well as connectivity in regions without cellphone reception would make it possible to permanently monitor these areas of interest. However, all these additional requirements should restrict the capabiliy of these sensors as little as possible when compared to expensive, large, traditional seismometers.

1.3 Goals

This thesis contains the following contributions:

- Feasibility evaluation of MEMS accelerometers for seismic sensing
- Investigation of characteristics which influence the capabilities of an accelerometer as a seismic sensor
- Development of a working prototype system, enabling the evaluation of MEMS accelerometers for seismic sensing.

Chapter 2

Background

To understand what capabilities are required of a seismic sensor, we estimate the properties of the signals that we are trying to detect and record in this chapter. Additionally, we contextualize the MEMS accelerometer in a range of sensors which are already used for seismic sensing.

2.1 Types of Seismic Signals

Exact assessments about the nature of the signals we are aiming to measure with our sensures are hard to aquire at this point. Frequency spectrum, amplitude and damping of the events are all hard to predict or estimate. Even though we are not exactly trying to detect seismic waves, we can get an idea about the frequency ranges from known seismic waves [6]:

- Teleseismic waves, earthquakes further away than 1000 km: 0.1Hz
- Local seismicity, earthquakes a couple km away: 10 Hz

We can see that the further away the event happens, the lower the frequency of the signals becomes, the rest becomes attenuated by the earth. It intuitely makes sense that the small events we are trying to detect are only measureable from quite close by, as otherwise their small amplitudes and relatively high frequencies quickly become dampened by the ground and indistinguishable from noise.

Different research has shown that while distance dampens high frequencies more than low frequencies, the size of the seismic event has a bigger effect on the spectrum [7]: A large earthquake produces lower frequencies than the small seismic events that we are interested in. This supports the hypothesis that a fine-grained sensor network is necessary to be able to record small seismic events, since they mostly consist of high frequency spectra which quickly get absorbed by the rock and become impossible to measure.

Not only seismic signals are of interest for the monitoring of mountain ranges, also the monitoring of glacial movements might be of interest, namely the following:

- Slow linear shifts: A couple cm per month
- Slow tilts: A couple degrees per month

These types of processes might again lead to events which produce signals that are similar to typical seismic signals when the destabilization increases the stress in the ice or rock enough to lead to sudden releases of tension, causing events like:

- Sudden "cracks": High frequency signals with quickly decreasing envelope.
- Rockfalls: Repeated shocks, again high frequency signals.

The spectra of cracks in solid rock have been found to be concentrated in the first 100 Hz, with a distance from crack to sensor of 10m [8], with a smaller distance possibly enabling the detection of higher frequencies. The spectra of rocks falls have been found to reach 50Hz [9], again with the caveat that higher frequencies might have been filtered out at the used measurement distances.

2.2 Types of Seismic Sensors

2.2.1 Mechanical Seismoscopes and Seismographs

Mechanical devices have been used for centuries to detect earthquakes. The earliest recorded example of such a device is Chang Hengs seismoscope, invented in 132 AD [1]. This device is reported to have been able to detect earthquakes and indicate the direction they occured in. As the suffix *-scope* implies, seismoscopes only indicate that a motion has occured, but neither its timing nor its magnitude.
Later examples include Forbes seismograph from 1844 [1]. This device consisted of a pendulum with a large stationary mass. In the case of an earthquake with lateral movement, the large mass remains stationary, creating a movement relative to the moving ground, which is recorded on a rotating piece of paper. This type of seismograph is still in use today. The suffix *-graph* means that the data is directly recorded by the device.
This basic idea of measuring the earths movement with a suspended mass which creates a relative movement against the moving earth has been a constant through centuries. The changes to the devices have included the size of the mass and the means of recording its movement.

2.2.2 Electromechanical Seismometers

Most modern devices fall in the category of seismometer, as they still use a proof mass to induce a signal based on the movement of the device. As they only produce a signal but don not record it, they are called seismo-*meter*.
Modern seismometers can be divided into four categories based on the method of measuring the movement or position of the proof mass [10]:

- **Geophones**: The magnetic proof mass is suspended by springs in a magnetic coil. When the proof mass is moved, it induces a voltage based on its velocity, which can then be measured with a voltage meter or digitized by an A/D interface.
- **Piezoelectric passive accelerometers**: The proof mass is suspended by piozoelectric transducers, which produce a voltage based on the pressure which is applied to them. The proof masses fall in the range between 0.1-1kg.
- **Capacitive passive accelerometers**: The proof mass is suspended by springs, and its position measured with capacitive displacement. The proof masses again fall in the magnitude between 0.1-1kg. However, this type of acceleromer can also be manufactured using MEMS technology, which reduces the proof mass by 3 orders of magnitude into the realm of milligrams. The energy uptake is reduced similarly.
- **Active accelerometers**: The acceleration acting on the proof mass is measured in the same way as in passive accelerometers, but the proof mass is suspended in the air by a coil, which is controlled based on the acceleration measurements. A devices called broadband seismometer usually falls in this category of functionality.

Accelerometers have either been too energy-intensive for independent, long-term use, or not sensitive and accurate enough in the case of MEMS accelerometers [5]. Technological advances in MEMS technology have improved their performance enough to reconsider them for this application, which is the subject of this thesis.

2.3 The Geophone Platform

During a prior project at the Computer Engineering Group (TEC) at ETH Zürich, a distributed sensor system called Geophone Platform (GPP) [11] has been developed. It uses a geophone to wake up the system and as a primary sensor, an ultra-low power Cortex-M4 core microcontroller for data processing, the dual-processor platform (DPP) [12] for communication, an LSM303C MEMS accelerometer and magnetometer as a secondary sensor, as well as additionally required circuitry such as a power controller and permanent storage.

Chapter 3

System Design

3.1 Problem Setting

We want to create a system that can detect and record seismic signals that are of interest for geomorphological research. The system should be able to meet these requirements at large scale without relying on external infrastructure, to make it possible to create a fine-grained sensor network with long service intervals. Apart from the capability to measure those signals, it also has to meet certain external requirements:

- **Low energy consumption**: The system should be able to operate for multiple years on one battery charge, because regular maintenance is impossible due to the remote location of their intended operation, and external power sources are not available.
- **Low cost**: In order to feasibly monitor a wide range of large mountainous areas, the cost of the system should be low.
- **Connectivity**: Important events need to be delivered to a central server, such that big events can be detected immediately. It also allows the user to assess the status and the measured data without having to collect the sensor first. This also allows us to record data at potentially unstable locations, where sensor nodes can be destroyed or lost.

3.2 Approach

The system needs a microcontroller to process the data delivered by the sensor. To save energy, the microcontroller goes to a sleeping state while no events are occuring. The accelerometer will be in a low power mode, ready to trigger the microcontroller when an event occurs. To be suitable for this approach, the sensor needs to have low power consumption, good sensitivity and accuracy of the measured data and the ability to generate interrupts based on a detected event. For the evaluation system, the effective energy consumption is secondary.

3.3 Choice of sensor

Accelerometer	Int. sensitivity	data bits	resolution [mg/dig]	low power [uA,Hz]	high power [uA,kHz]	noise density [ug/Hz]
ST LSM303C	8 mg	16	0.06	50,10	180,0.8	1000
ST LIS3DSHTR	8 mg	16	0.06	11, 3	225,1.6	150
ST AIS328DQ	16 mg	12	0.98	10,50	300, 1	218
ST IIS2DH	16 mg	12	0.98	2, 1	185,5.3	?
ST IIS2DLPC	-	14	0.244	0,038	130	90
Bosch BMA 280	-	14	0.244	6,5	130	120

In the table above, a selection of compared ultra-low power MEMS accelerometers can be seen. For all of them, the smallest configurable measurement range has been evaluated, typically [-2g, 2g]. Between them, the ST LSM303C shares first place for both interrupt sensitivity and output data resolution. It is respectable in terms of power consumption, also at higher sampling rates. As the only one of the presented sensors, it also includes a magnetometer which can be separately switched on and off, potentially recording additional valuable information, such as the absolute rotation of all three axes.
However, the noise density of the LSM303C is strikingly high in comparison with other sensors. This needs to be kept in mind for the evaluation.
At a medium sampling rate of 100Hz, the expected noise will be 0.1mg, enough to change the one or two least significant bits of the output data, but far from affecting the interrupt generation. At its maximum sampling rate of 800Hz and an expected noise level of 0.8mg, we expect to clearly see the noise in the output data, but it alone should be too little by a factor of 10 to to set off a false positive interrupt. However, as we can see in section 5.1, false positives do occur at the higher sampling rates. However, it remains unclear if noise from the sensor is the cause.
After these considerations, it seems unlikely that the noise density will negatively affect the performance of the LSM303C for our application.

Using the LSM303C for our evaluation has another invaluable advantage for us: As has been discussed in section 2.3, we have access to the GPP, a complete working system which already includes the LSM303C. This simplifies and accelerates the task of evaluating its performance, and developing software which will be directly usable on a future stand-alone system. Additionally, the findings and the software of this thesis can easily be used to improve the data collection of GPPs which are already in use in the field or will be deployed in the future.

3.4 Required Hardware

Three essential components are necessary to evaluate the performance of the LSM303C: The LSM303C itself, a microcontroller with sufficient processing power, and permanent storage. The GPP fulfills all our requirements, so we can use it unmodified.

Chapter 4

Implementation

In this chapter, the implementation of the evaluation platform is described. As is described in Section 3.4, an unmodified GPP is used as a hardware platform, so we focus on the software modifications in this thesis and refer to previous work for details on the hardware. A detailed documentation of the used hardware can be found in the GPP thesis [11].

4.1 Software Overview

Since most of the peripheral functions of this system are identical with the GPP, the software for this project was also based on the GPP software. We modified the existing code by deactivating all systems related to the geophone, and rewriting the IMU handling task completely.
The removal of the ACQ task, which was responsible for handling data acquisition from the geophone, made it necessary to design the IMU task to operate completely independently from other tasks once started and initialized. The interrupts it receives from the LSM303C constitute the only external influence. Additionally, configuration and logging had to be adjusted to support new features and data types.

4.2 Accelerometer operation modes

The most critical factor on the whole systems performance is how well the capabilities of the LSM303C are utilized. The accelerometer and the magnetometer on the LSM303C can be configured and used in a plethora of ways. We explored many ways to configure the sensor. Two main operation modes have been developed, the two of which have a different main focus: The "high pass filter mode" aims to sense vibrations in a very consistent, simple and robust way. The "reference mode" can detect changes in inclination, irrespective of how slow that

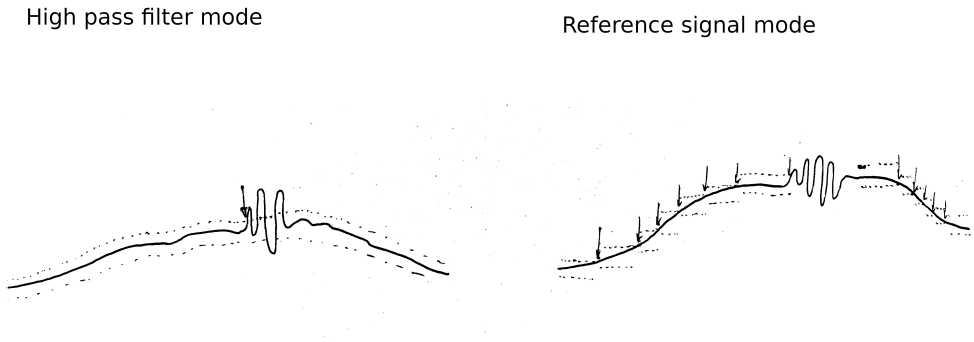

Figure 4.1: Number of triggers of reference mode vs high pass mode.

change happens, which can be seen in figure 4.1. In both modes, certain characteristics, mainly the sampling rates of inactive and active operation, can be adjusted during operation.

4.2.1 Triggered high pass filter mode

The goal of the high pass filtered operation mode is to optimally use the accelerometer to detect relatively high frequency, transient local seismic signals. The built-in high-pass filter offers a simple and reliable way to return the signal on all axes to zero when the sensor is at rest, filtering out the static measurement of the gravity, and all sensor offsets. This makes the process very straightforward and robust, since the threshold of the interrupt generator doesn not need to be adjusted during operation. This reduces energy consumption, downtime after an interrupt, and avoids glitches due to wrong thresholds or other unforeseen effects.

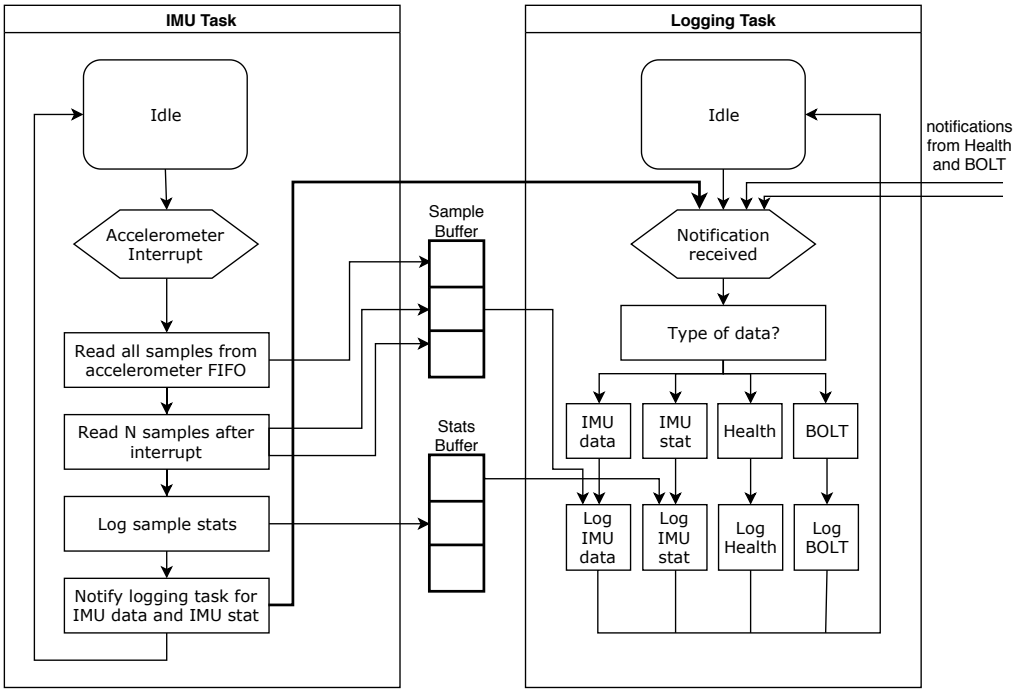

Figure 4.2: Accelerometer sample recording in high pass mode.

4.2.2 Reference mode

The reference mode utilizes the reference signal functionality of the LSM303C. This allows us to not rely on a high pass filter to remove the static position of the sensor, but manually set a fixed reference signal, which is subtracted from the output signal, which can be seen in 4.3. This means that no matter how slow the angular position of the sensor changes, the sensor output will eventually exceed the set threshold and produce an interrupt.
This functionality should provide more information in situations where not many rock falls or other events produce high frequency signals, but slow destabilisation, shifts and deformations can give us information about processes like the destabilization of rock glaciers. However, it necessitates careful setting of the reference signal. This process requires multiple reconfigurations of the sensor, and takes longer than simply logging the measured values and immediately returning to an idle state. Consequently, the downtime after an interrupt is longer.

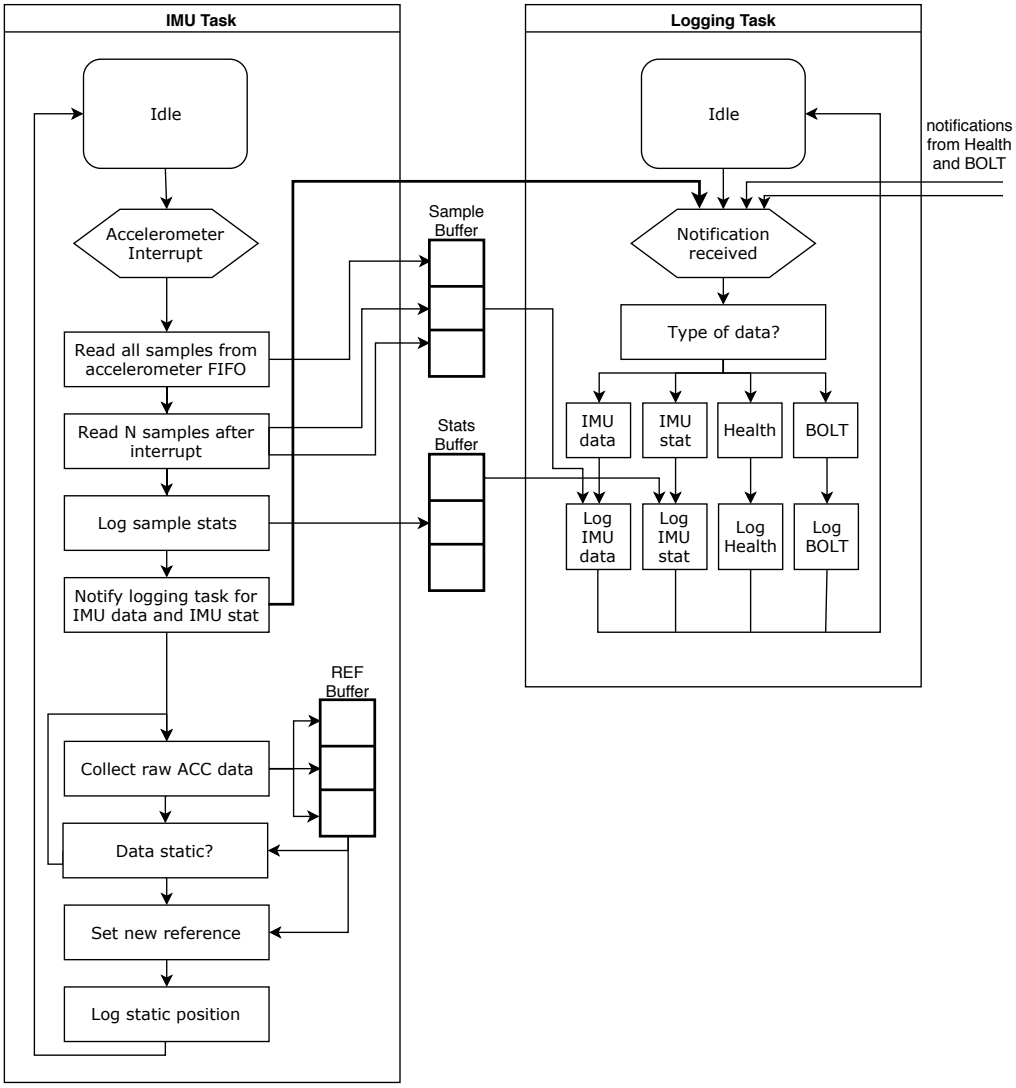

Figure 4.3: Accelerometer sample recording and reference signal recalculation in reference mode.

Chapter 5

Evaluation

The system has a set of very different tasks: Detecting high frequency, transient vibrations and detecting slow changes of position over time. These requirements were tested separately.

5.1 Testing high frequency sensitivity

To test the performance of the two operation modes in regards to high frequency signals, we cause reproducible shock vibrations in an array of materials with different characteristics in regard to sound propagation.

5.1.1 Comparison of sampling frequencies in high pass mode

The goal of this test was to get a good estimate for the capabilities of the sensor and the effect of the different sampling frequencies in the low power mode. The task was to sense a relatively strong shock with a moderate resonant frequency. This was created by hitting a table with a fist vertically lightly. The accelerometer was configured in all available sampling frequencies: 10Hz, 50Hz, 100Hz, 200Hz, 400Hz, 800Hz. After creating an interrupt, the microcontroller set the post-trigger sampling frequency to 400Hz for all configurations.
A huge difference in performance could be seen. At 10Hz, the accelerometer didn't produce an interrupt at all. On the other hand, as we can see in Figure 5.5, the accelerometer nearly reached its maximum of 2g at 800Hz. However, also an increase in noise could be observed. At sampling frequencies 400Hz and 800Hz, the accelerometer kept producing an interrupt without consciously created or perceptible vibrations. This can be alleviated by increasing the threshold of the interrupt generator.

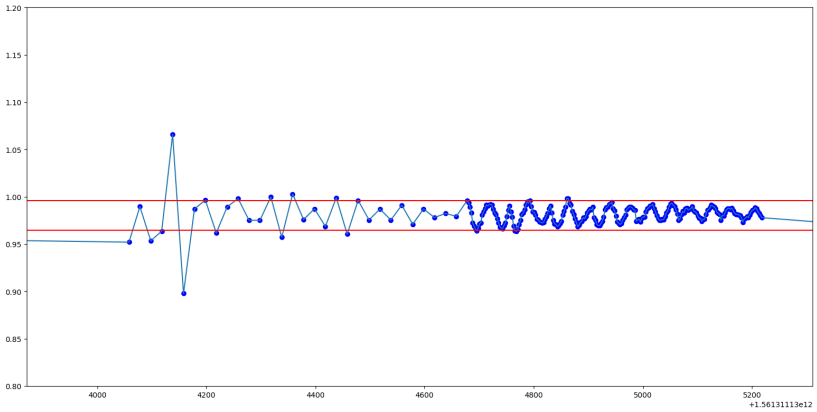

Figure 5.1: The produced signal of the 40Hz test, at 50Hz sampling frequency.

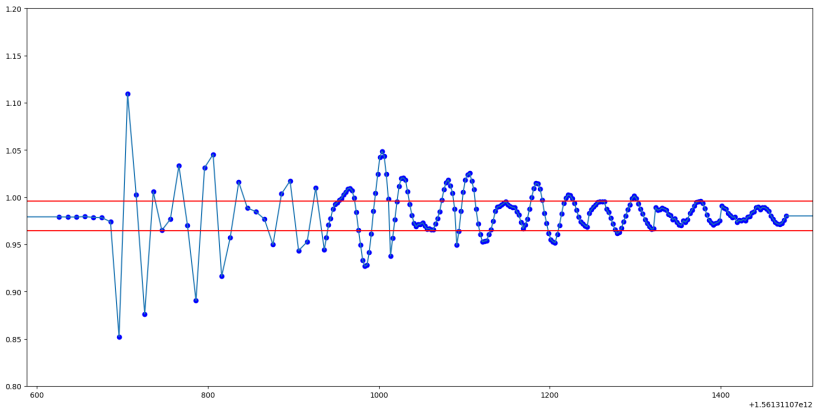

Figure 5.2: The produced signal of the 40Hz test, at 100Hz sampling frequency.

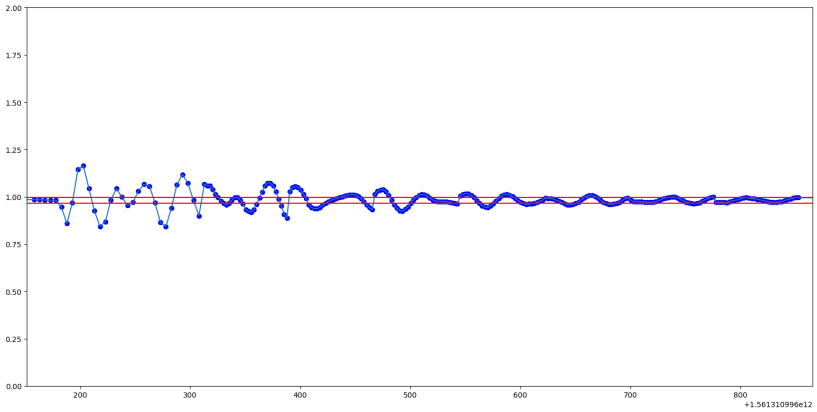

Figure 5.3: The produced signal of the 40Hz test, at 200Hz sampling frequency.

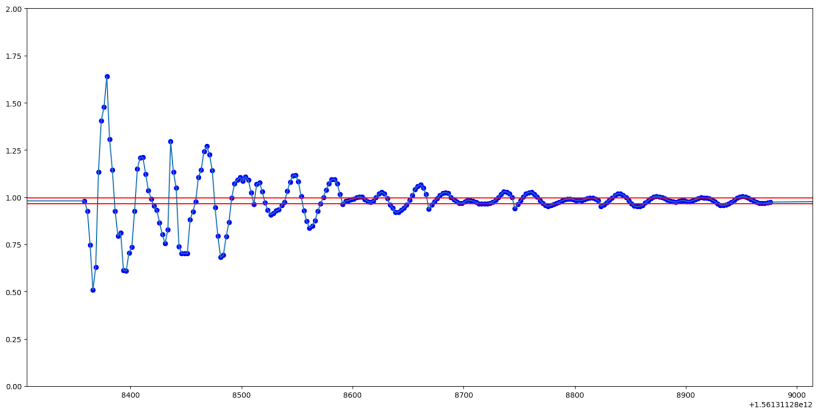

Figure 5.4: The produced signal of the 40Hz test, at 400Hz sampling frequency.

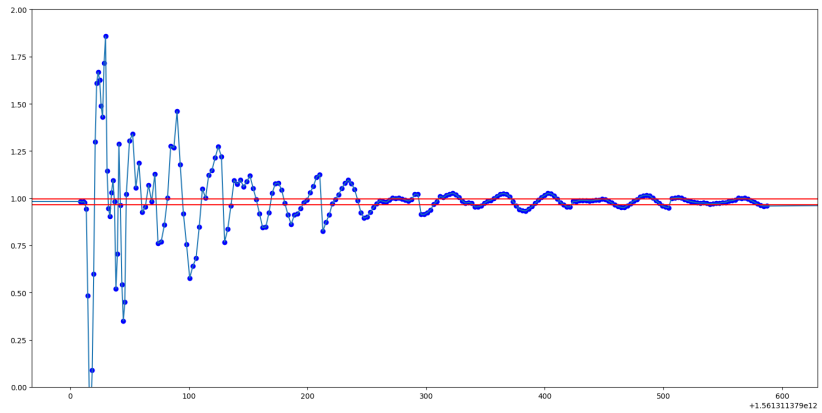

Figure 5.5: The produced signal of the 40Hz test, at 800Hz sampling frequency.

5.1.2 Comparison of high pass mode against reference mode

To compare the performance of the high pass filter mode and the reference mode for high frequency signals, the same test as above was repeated with two GPPs, one configured in high pass filter mode, the other in reference mode. As can be seen in figure 5.6, their performance in this task is very similar.

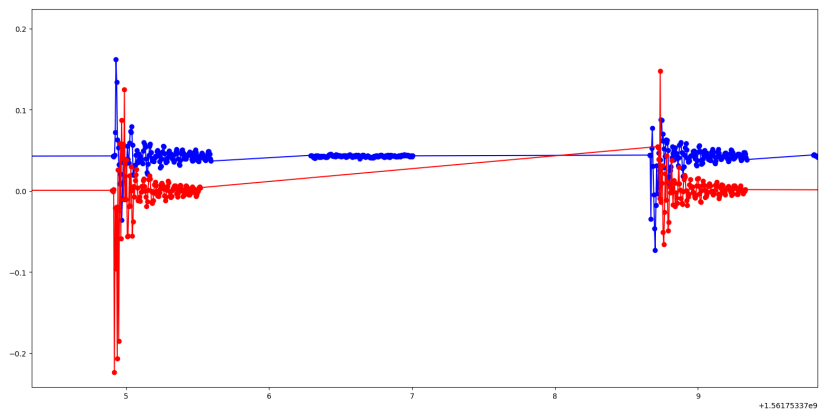

Figure 5.6: The resulting signals of a shock at 200Hz. Blue: High pass filter mode, Red: Reference mode.

5.2 Testing slow angular changes

5.2.1 Number of interrupts during slow tilt

To test the performance of the two modes in detecting tilting movements, the sensor node was tilted slowly in one direction. It proved to be quite easy to carefully tilt the GPP slow enough not to trigger the one configured in the high pass mode, so as we would expect, the high pass filter mode is unable to detect slow changes in angular position. However, the reference mode performs very well. The slightest tilt that can be performed manually is detected, and the new position is logged.
As can be seen in figure 5.7, the absolute value of static measurements of the X axis are increased while the GPP is tilted in its direction, while the acceleration measurement in Z direction is decreased.
Additionally, the dynamic measurements, i.e. the values from which the reference signal has been subtracted, can be seen to increase, respectively decrease steadily until the a new reference signal is set, which causes it to return to zero. This effect can be better seen in figure 5.7, where only the accelerometer values of the X axis are shown.

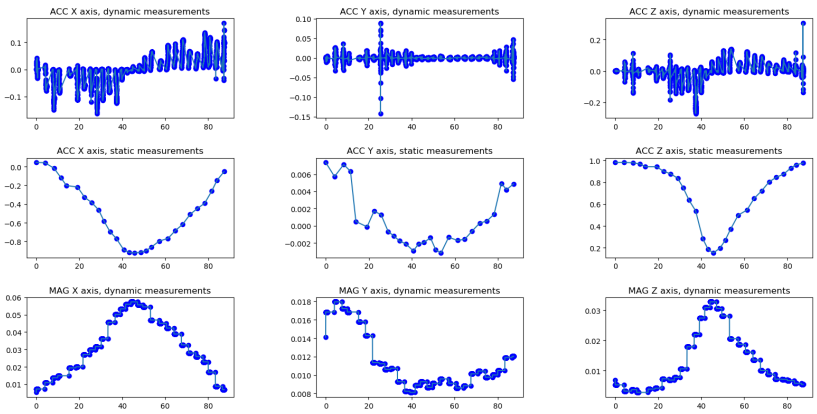

Figure 5.7: All output signals while performing a 90°tilt in one direction and back.

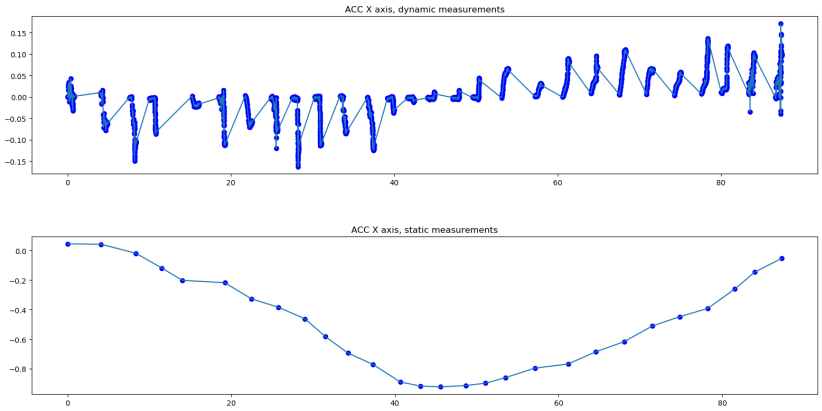

Figure 5.8: The dynamic and static acceleration values in the X axis of the data shown in figure 5.7.

To assess the sensitivity and accuracy of the reference mode, the GPP was again tilted from a flat position to 90°to one side, this time as slowly as manually possible . This can be seen in figure 5.9.
This slow tilt over 90°resulted in over 200 logged static positions. This means that less than a 0.5°of change of angular position will be registered by this mode of operation.

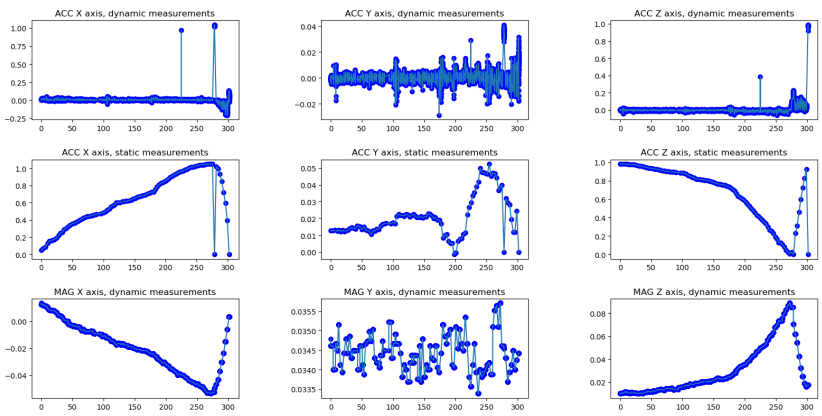

Figure 5.9: The measured data of a tilt that was performed as slow as possible.

5.3 Power Measurements

Power measurements were performed with a rocket logger [13]. However, due to the micro-controller going to the low-power mode and using busy cycles inconsistently, the recorded data could not be utilized to confidently determine the power usage of the system in different operation modes and sampling frequencies at this point.

Chapter 6

Conclusion

After outlining the types of seismic signals that are useful to detect and putting MEMS accelerometers into context with existing types of seismic sensors in Chapter 2, we defined the necessary characteristics of a stand-alone MEMS seismic sensor platform. We found that the GPP had all the necessary components to evaluate the feasibility of such a system.
The implementation described in Chapter 4 focused on the way that the MCU interacts with the accelerometer to offer operation modes focused on different focus in terms of signal to be measured.
The high pass filter mode uses the built-in high pass filter in the LSM303C to remove the static angular position from the signal which is used to generate the interrupt. This results in a very simple, robust and consistent operation, offering good performance for the detection of seismic waves with spectra lower than the sampling frequency.
In contrast, the reference mode explicitly measures its static angular position after each interrupt, resulting in the ability to detect angular changes independent of the angular rate, at resolutions of less than 0.5°.

6.1 Findings

In chapter 5, we saw the Nyquist theorem in action, but with a twist: As we would expect, sampling rates lower than the frequencies of the signals we are trying to measure results in bad performance. We would expect the accelerometer randomly catch a spike of a high frequency signal and cause an interrupt from time to time, but we have never observed this during our experiments.
Further increasing the sampling frequency results in diminishing returns, but still results in better and better sensitivity. However, at the highest sampling frequencies, the comparatively high noise level of the LSM303C becomes noticeable and affects signal quality and causes false interrupts.

6.2 Future Work

- **Incorporating the reference mode to existing GPP nodes** and validating its value in field conditions. As the ability to detect high frequencies is irrelevant in the combined platform, the reference mode can be used in its lowest power setting and add the valuable ability to detect changes in angular position.

- **Evaluate additional accelerometers** which are more narrowly tailored to the respective application, using the finding of this thesis: Low power consumption at high ODR, sensitive interrupt generation, low noise all have proven to constitute benefits for this platform.
  Looking back at our table of choice of sensors in section 3.3, the ST LIS3DSHTR seems like a promising candidate. With its considerably lower noise and lower power consumption relative to the sampling frequency, it might be the next step up from the LSM303C for seismic sensing.
  Even the ST IIS2DH might be an interesting candidate. Despite its slighty worse interrupt sensitivity, its huge range of sampling frequencies for low power budgets might open new possibilities.
  A lot of experimental potential is still open as well. Experimenting with exactly defined signals, exactly measuring the the angular sensitivity of the reference mode, power analysis: Many questions can still be answered to more accurately estimate the potential of the MEMS accelerometer.

- **Development of a stand-alone MEMS accelerometer sensor platform**. After collecting real-life data with the existing GPP nodes, and finding the ideal MEMS accelerometer, developing a stand-alone platform is the logical next step, to leverage its low cost and size.

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