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ENERGY HARVESTING FOR INDUSTRY 4.0 APPLICATIONS
ENERGY HARVESTING PRO VYUŽITÍ V PRŮMYSLU 4.0

BACHELOR'S THESIS
BAKALÁŘSKÁ PRÁCE

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Bachelor's Thesis Specification

25202

Student:	**Gajdošík Róbert**
Programme:	Information Technology
Title:	**Energy Harvesting for Industry 4.0 Applications**
Category:	Embedded Systems

Assignment:

1. Investigate and survey existing means of energy harvesting and ultra-low power systems for industrial use.
2. Familiarize yourself with methods for data collection from sensors, information filtering, and processing.
3. Design and implement a system that will integrate the energy harvesting paradigm into the process of data transfer and collection from industrial sensors.
4. Evaluate the behaviour of the system and discuss its suitability for real industrial applications.

Recommended literature:

- as suggested by the supervisor

Detailed formal requirements can be found at https://www.fit.vut.cz/study/theses/

Supervisor:	**Smrž Pavel, doc. RNDr., Ph.D.**
Head of Department:	Černocký Jan, doc. Dr. Ing.
Beginning of work:	November 1, 2021
Submission deadline:	July 29, 2022
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Abstract

The aim of this thesis is to estimate industrial applications of energy harvesting in industry 4.0. As a part of this project, a working prototype was constructed using a piezoelectric harvester and appropriate sensory equipment. A vibration sensor was chosen as the most appropriate solution for measuring vibrations emanated by the object being observed. Subsequently, a software solution was developed for calculating the frequency of the vibrations using analog sensor input handled by an analog-digital converter. The result is a tested prototype of a self-powered sensor capable of sending warning messages when detecting anomalous vibration frequencies emanating from the monitored object.

Abstrakt

Cieľom tejto práce je demoštrácia možností využitia energy harvestingu v priemysle 4.0, so zameraním na prototyp samonapájacieho vibračného senzoru. Vrámci práce bol vykonaný výskum techník pre zhromažďovanie a spracovanie dát ako aj výskum ohľadom senzorového vybavenie budúceho prototypu.

V ďalšom kroku bol vykonaný výskum a získaný prehľad ohľadom energy harvesterov, metód presunu a manipulácie vyťaženej elektrickej energie, a spôsobu jej uchovania. Ďalej bol vybraný vhodný mikroprocesor s vhodnou výbavou ohľadom vstupu a výstupu napájania, energie a konektivity. Nakoniec implementácie boli vyriešené rozhrania medzi jednotlivými komponentami prototypu.

Po vyhodnotení ďalšieho postupu bolo rozhodnuté vyvinúť software pre plánované rozhrania medzi senzorom a procesorom, ako aj spracovávanie dát za použitia vzorkovania a rekonštrukcie analógového signálu za použitia analógovo-digitálneho meniča. Ďalej bola vyvinutá jednoduchá časť software pre detekciu anomálií v očakávaných frekvenčných pásmach daného objektu, a otestovaný jednoduchý kód pre využite subsystému BLE. Nakoniec tejto časti projektu boli preskúmané možnosti vylepšenia účinnosti využitia energie použitej pre napájanie mikroprocesora.

V poslednom kroku práce boli otestované všetky komponenty navrhnutého prototypu. V prvej časti bola otestovaná funkcionalita komponentov bez integrácie s ostatnými časťami systému. Bola testovaná presnosť vibračného senzoru, funkcionalita harvesteru, a otestované jednotlivé subsystémy mikroprocesoru. V druhej časti testovania boli testované interakcie jednotlivých komponentov, napríklad rozhranie medzi mikroprocesorom a vibračným senzorom, a testovanie korektnosti softvérových metód pre vypočítanie frekvencie monitorovaného objektu. V poslednom kroku testovania boli otestované množstvá enegie vyťažené piezoelektrickým efektom a porovnané s experimentálne overeným odberom energie kompletného obvodu. Následne boli tieto informácie využité k aproximácií ceny prototypu a jeho realizovateľnosti v praktickom priemyselnom prostredí.

Výsledkom práce je funčný prototyp obvodu samonapájacieho vibračného senzoru a teoretický návrh efektívnejšej verzie založenej na experimentálnych metódach prenosu energie medzi harvesterom a úložistom energie, ako aj aproximácia jednotkovej ceny obvodu a vyhodnotenia jeho použiteľnosti v modernom priemysle.

Keywords

energy harvesting, self-powered sensor, piezoectricity, vibration, frequency calculation from analog input, energy harvesting feasibility, industry 4.0, prototype

Klíčová slova

energy harvesting, samonapájací senzor, piezoelektrina, vibrácie, výpočet frekvencie z analógového vstupu, realizovateľnosť energy harvestingu, priemysel 4.0, prototyp

Reference

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Energy Harvesting for Industry 4.0 Applications

Declaration

I hereby declare that this Bachelor's thesis was prepared as an original work by the author under the supervision of Mr. doc. RNDr. Pavel Smrž Ph.D. The supplementary information was provided by Mr. Ing. Václav Šimek. I have listed all the literary sources, publications and other sources, which were used during the preparation of this thesis.

. . . .
Róbert Gajdošík
July 29, 2022

Acknowledgements

I would like to thank Mr. doc. RNDr. Pavel Smrž Ph.D. for his open mindedness when deciding on a theme for this thesis and his patience and forthcomingness when dealing with the health issues present during the making of this thesis. I would also like to thank Mr. Ing. Václav Šimek for providing crucial information during the early stages of the project. Finally i would like to thanks DCGM FIT for providing access to the hardware necessary to facilitate the experiments performed in the making of this thesis.

Contents

Chapter 1

Introduction

Automation and gathering of data are one of the fastest developing trends of the current decade. One of the more specific fields is gathering a large amounts of data for the purposes of tracking, efficiency monitoring, failure prediction, damage control and many others. This task has a number of component sub-tasks, such as the gathering of data itself and the subsequent processing and reporting. One of the most important problems is ensuring the collection of the data to be precise, unobtrusive, and accurate.

The driving force behind this thesis is an attempt to gain the ability to accurately collect data from specific locations with no downtime, should it be deemed necessary, so that this data can be used to improve a machine's efficiency, provide an early warning in case of an approaching catastrophic failure, or give an instantaneous report if such a failure has already occurred.

This thesis is working with a presupposition that the object of interest is generating vibrations either at all times, or during it's active period, such as a machine's active daily cycle in a factory. This object is a constant source of vibrations, the range of which is known to us either by observation and testing or from information provided by the object's manufacturer's data sheet or manual. This vibration needs to be monitored, for any unwanted change in any of it's physical quantities such as displacement or frequency might be a sign of material wear or mechanical damage present in the object[25]. It is also a source of power for the system, as with the latest technologies we can harness it's kinetic energy, which is usually a bi product of either material strain, as is the case with bridges and or wind turbine's fan blades[20], or some sort of internal movement, such as during an engine's operation. This theoretically allows us to power the device, the task of which is to collect and process, possibly send reports about the data collected, at all times, without needing periodic direct access for recharging or replacing the power source.

The solution is based on piezoelectric bending transducers[23] mounted on a surface of, or incorporated into, the object we are monitoring. These devices convert vibrations emanated by the object into electrical charge. This powers a battery or a super-capacitor, which in turns stores power for both the sensor and the micro-controller unit. The data collection is the responsibility of the vibration sensor, which is mounted on a surface and reports the frequency of the vibrations emanating from the object. These are then sent into a micro-controller unit. This unit then compares the data gathered with the specifications of the object, and reports any found discrepancies using low power communication protocols to any device designated as the central unit which reports these findings to the relevant personnel or possibly further automatized contingency systems already in place.

The result of this thesis is a working prototype of a self-powered sensor device capable of gathering data and reporting on any anomalies detected by the sensor. The functionality is proven by testing the components of a system to see if they are working as expected individually, and then testing the complete system with a number of devices that produce a predictable range of vibrations. This information is then used to evaluate the practicality of deploying a network of these devices allowing the observation of the object from different places or multiple objects independently of each other.

Chapter 2

Data gathering and manipulation

This chapter introduces the means of gathering data pertaining to the object of interest 2.1, and then outlines several means of encoding 2.2 the data in order to manipulate and make use of it 2.3.

Concept of gathering and processing data

Data gathering is a process of capturing physical or digital properties of a specific object using specialized equipment. In this case, the device is observing the frequency of an object either by mounting it on the surface or incorporating it into the object itself. This data is then manipulated by other analog or digital components and combined with outside knowledge and context to evaluate the object's state and further provide more information that was not readily apparent from the raw data gathered.

2.1 Sensors

For correct monitoring of the object for the purposes highlighted in the introductory chapter, it is necessary to secure enough information about the state of the object. There are multitudes of attributes that can be monitored by the sensory equipment of a device, and conceptually it is not necessary for the sensor to be observing the vibrations emanated by the device, as they can be used merely as a power source for the device, and not necessarily the only attribute of interest. We can sort these sensors into two groups:

- sensors monitoring the internal state of the object,
- sensors monitoring the environment around the object.

Sensors monitoring the internal state of the object

Internal state of the monitored object may be indicated by several attributes including internal heat generation, vibration and electrical attributes of internal circuits such as voltage and current.

This can be achieved by sensory equipment such as a digital thermometer, multimeter, accelerometer and many others. These attributes might be an excellent source of information about possible dangerous events occurring such as internal overheating, short-circuits or subsystem power failures.

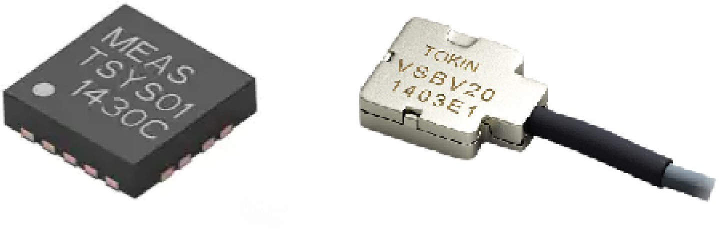

Figure 2.1: From left to right: TE G-NICO-018 thermal sensor [7], Kemet VS-BV203-B vibration sensor[8]

Sensors monitoring the environment around the object

External environment may also be of interest when dealing with, for example, operational safety of a machine. The prevalent attributes of interest in this regard are, temperature, humidity and wind speed.

This kind of monitoring can be used in cases of a device being too sensitive to low or high temperatures the best example at hand being the energy harvester used in this very device, vulnerable to high humidity such as circuits with insufficient ingress protection rating, or in danger from forces exerted by high wind speeds such as wind turbine blades.

Figure 2.2: Adafruit analog output anemometer wind speed sensor[1]

Some more advanced techniques include using either a net of sensors[19] of the same type scattered around or inside the monitored objects, or using a multitude of different sensors measuring completely different attributes altogether, forming a complex lookout system for any potential dangers to the object in question by intertwining multiple sources of information provided from multiple different attributes.

2.2 Data input

In order to process the data recorded by the sensory equipment, it may be necessary to employ different types of equipment to handle the output. The output data of the sensor may already be digital if the sensor is automatically encoding the data measured internally, in which case it is not necessary to delegate this function to another component in the device. If this is not the case however, as is the case with the solution provided by this thesis, it is necessary to convert the analog data provided by the sensor to a digital format in order to be further utilized using an analog-digital converter. This device compares an analog value input to a reference value set by the device's attenuation, and then calculates the real value present at the input and samples it in a time domain, forming a discrete digital signal.

The reason for encoding the data into a digital format is to be able to record, compare and manipulate it. Conceptually, this step is optional, entirely depending on the sensing equipment responsible for data gathering, however in this specific case it is necessary to digitize data provided by the sensor.

Sensor output

The Kemet VS-JV10A sensor outputs a continuous signal with a reference voltage of one half that provided by the power supply. However, when in the process of measuring vibration, the signal is constantly changing and owing to it's analog nature the precise voltage could be represented with an infinite number of decimal points at an infinite number of points in time. In order to extract useful data from, interact with, and manipulate the signal it is necessary to sample it and convert it into a digital value.

Signal conversion precision

When converting a signal from analog to digital format, it is important to realise how much precision is necessary to achieve when measuring a physical attribute. When dealing with sensor outputs that vary output voltage, the micro-controller used would be able to convert it to digital format up to 12 bits long[17].

$$resolution = \frac{(V_{max} - V_{min})}{2^{bitrange}}$$

Using the reference minimum and maximum voltage of 0 to 3.6 volts this gives us the resolution of about 800 μA. The bit length can be reduced to 10 or even 8 bits however the resolution decreases as a result. This results in a compromise between memory intensity of the application and the precision at which the micro controller calculates the duty cycle, as the truncation error might introduce a problem where the reported voltage might be lower or higher than the actual analog signal reports resulting in an inaccuracy in the voltage period calculation due to incorrect threshold detection.

Another part of data manipulation is also communication with other devices as a reaction to conditions created by data processing, examples being a simple sending of a warning or a constant stream of information to another device responsible for the entire sensor network.

2.3 Data manipulation

With the data now able to be utilized, it is important to select the device handling the ADC output. This can be a generic processor, or a more specialized type of input handling equipment commonly used in cars and industrial applications such as a field-programmable gate array, which while being more energy efficient is also overspecialized, which may be a disadvantage if one were to decide to change the method of processing the data in the future.

Data utilization might have many forms, from simple comparison with a predetermined value or a range of values, such as a machine's safe operating temperature, to archiving or passing the data along to another device.

The manipulation of data is achieved depending on the conditions set by the device's intended user, such as comparing to a range of values set as standard operating frequencies of the object in question, or recording and archiving data for the purposes of future analysis. It should be noted however, that the more requirements on data handling, the price of the device may increase as recording and archiving of data requires more power than for example a simple comparison, even if one uses non-volatile memory.

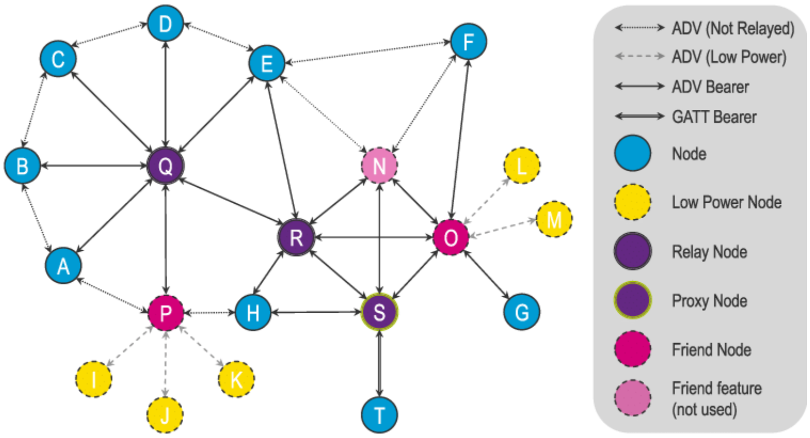

Figure 2.3: BLE mesh with both low power and standard bluetooth auxiliary nodes[18]

Another sub-task of data manipulation is also communication with other devices as a reaction to conditions created by data processing, examples being a simple sending of a warning or a constant stream of information to another device responsible for the entire sensor network. This can be achieved by, for example, a master BLE or LoRa server or receiver located in a close proximity of every sensor node in the network, or being in a different location utilizing hopping between full power bluetooth nodes external to the sensor nodes until reaching the master device.

Chapter 3

Device implementation

This chapter introduces the final implementation of the device including the power source 3.1, the power management system including methods of power transfer 3.2 and power storage and delivery 3.3, the sensor 3.4 and the data processing device 3.5, and discusses the reasoning behind why these specific parts were chosen, and possible alternative solutions.

3.1 Power source

Device configuration

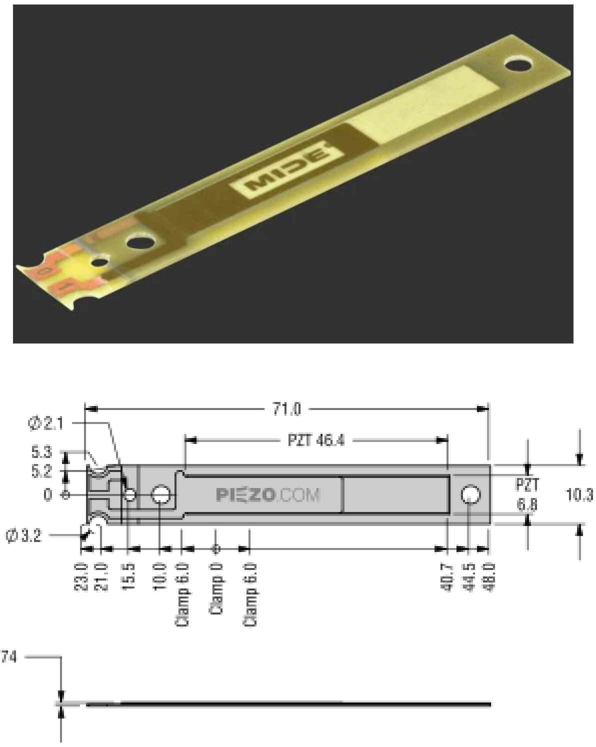

Figure 3.1: From top to bottom: S129-H5FR-1803YB Piezoelectric Bending Transducer and it's dimensions[13]

Supplying power to the device is a S129-H5FR-1803YB one-layer piezoelectric bending transducer in a cantilever beam configuration. This transducer generates electrical charge when when acceleration is applied along the z-axis of the device causing the cantilever beam to bend.

Because of the nature of the cantilever beam deflecting back and forth around it's resting point in a sine wave pattern when observed in a time domain, it generates an alternating current. Since the rest of the device is only compatible with direct current, it is necessary to employ a four diode full wave rectifier to convert the alternating current to a direct one. The reasoning behind the cantilever design is the ability to add tip mass to the beam to adjust the frequency and amplitude of the beam deflection potentially aligning it with the harvester's resonant frequency optimizing the power output[22].

Possible alternative

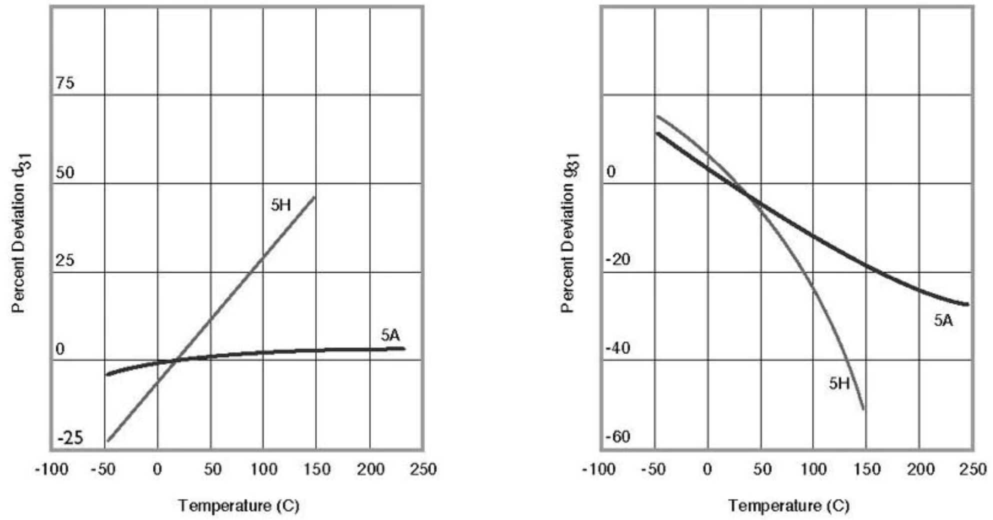

Figure 3.2: Piezoelectric coefficients' dependence on temperature levels[12]

A possible alternative for the harvester is any harvester that is composed from a PZT-5A material as opposed to PZT-5H present in the harvester used in this thesis. The advantage of the 5A material is it's performance is temperature invariant whereas the 5H material is inferior in charge generation deviating approximately half a percent of it's piezoelectric coefficient per degree Celsius starting at 10 degrees Celsius and below, however it also outperforms 5A by the same margin for every degree Celsius above the aforementioned threshold.

3.2 Power transfer

There are two major issues to solve regarding the transfer of energy between the harvester and the battery. The first issue is that the rest of the circuit and it's components operate on direct current as opposed to alternating current that the harvester produces, also the power storage solution, in this case a battery needs a charging voltage of up to 4.2 volts to get charged to it's full capacity.

Current conversion

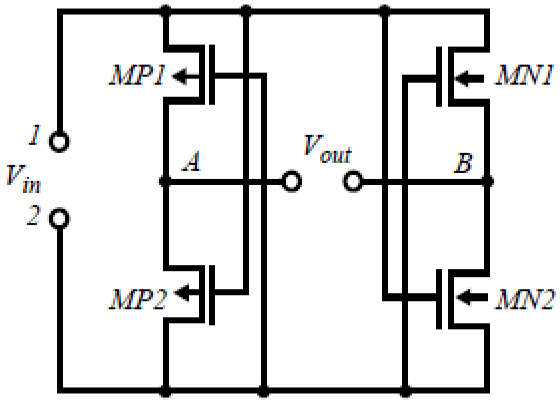

Figure 3.3: CMOS integrated full wave rectifier - negative voltage converter[21]

In order to utilize the energy provided by the harvester we need to convert it from alternating to direct current first. Due to shortage of time, this part is purely theoretical, however, using a proposed design on a CMOS Integrated Full Wave Rectifier[21], we should be able to reach voltage rectification efficiency above 70% of the original output at all times, with efficiency high points of up to 90%. This is also cheaper and less space intensive than a center tapped transformer rectifier, as the design only uses small CMOS transformers and diodes.

Voltage step-up

Since the charge end voltage requirement of the battery used in this thesis equals to 4.2 volts, and unless we want to, in the case of one of the tests described in a later chapter involving an electric motor powered lawnmower, use around 14000 harvesters in series, it becomes necessary to use a step-up voltage converter.Using some of the newest experimental step-up voltage converters, this step of the process could reach anywhere from 92.1% conversion efficiency upwards[24].

3.3 Power storage

Figure 3.4: Ansmann Li-Ion battery 18650[2]

Battery configuration

For the battery the system is using the Ansmann 18650 rechargeable lithium-ion battery. The battery delivers a peak voltage of 3.6 volts while having the endurance of 2600 mAh. This voltage allows us to deliver a voltage slightly above the minimum voltage requirement of both the sensor and the micro-controller unit, while retaining a relatively small form factor, albeit being on the heavier side compared to other batteries of lower capacities and having a lower power density than comparable capacity supercapacitors.

Possible alternatives

Figure 3.5: Eaton XT Large Cell Supercapacitor[4]

For the power storage alternatives, since the leading paradigm of this prototype is the ability of sustaining itself indefinitely, it is possible to replace this battery with a different one of smaller capacity, since the device is not designed to run without a supply of power for a long period of time. A possible second alternative is possible with the recent breakthrough in capacitor technology called supercapacitors, which offer a significantly smaller form factor while also being significantly lighter, while offering a significantly increased number of charge/discharge cycles[16].

The problem that needs to be addressed when it comes to supercapacitors is the fact that they rapidly lose voltage while being discharged, which might necessitate using multiple supercapacitors in parallel to ensure high enough voltage for our device components to remain functional if a scenario where the capacitors would lose more than 75 percent of their charge would occur.

3.4 Sensor

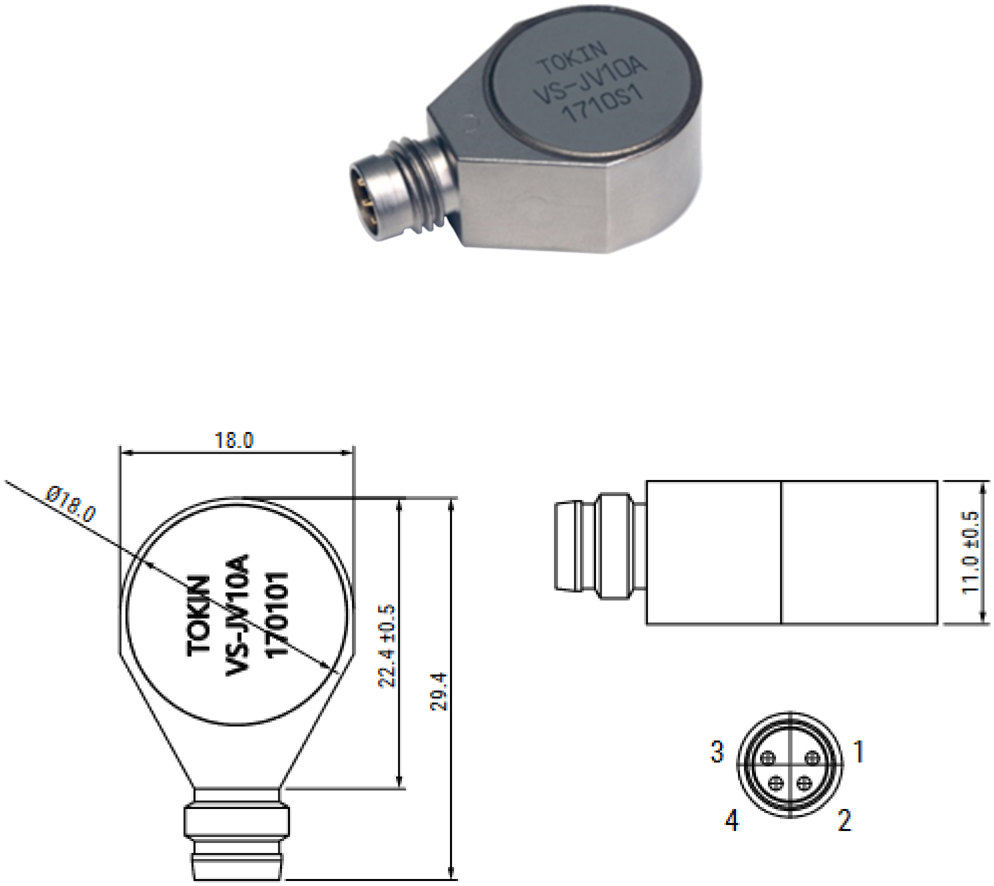

Figure 3.6: From top to bottom: Kemet VS-JV10A vibration sensor and it's dimensions[9]

Sensor configuration

The device is equipped with the Kemet VS-JV10A Vibration sensor. This sensor is able to detect vibrations in a range of 10 to 15000 Hertz[10] while having an ingress protection rating of 67 which is particularly important in some factory operations where there might be high concentrations of dust, or in environments with flowing or spraying water due to various machine cooling solutions.

The sensor's minimal power supply voltage is rated at 3.2 volts which is low enough to be powered by the 3.6 volt power supply. The operating temperature range is between -25 and 85 degrees Celsius which is adequate since the main temperature constraints are imposed though the safe operating temperature of the lithium-ion battery. It has the option to be connected with an M8 cable however in testing the power input, output and the sensor output were connected by a standard copper wire with plastic isolation. As per product instructions the sensor output is furnished with a 100 kΩ load resistor to prevent the overloading of the micro-controller unit's input terminal.

The reasoning behind deciding on this particular part is due to it's attributes satisfying the low power and small form factor of the sensor note, the device being rated at draining 500 μA and the limited availability of other products during the time of picking parts for the node prototype.

Possible alternatives

From the model of sensor chosen for this particular work it is apparent that the primary focus is the measurement and exploitation of vibration. However, as outlined in chapter 2, there are many more physical aspects worth measuring depending on the object of interest and the purposes the data collected is being used for. Sensory equipment designed to track temperature, wind speed, current, voltage and many others could have just as easily been used as replacements for the sensor used in the prototype, however this may come at a cost of reducing the amount of feasible placement locations, for example it is fairly obvious that an anemometer because of it's intended use is not suitable to be enclosed in the concrete part of a bridge construction.

3.5 Micro-controller unit

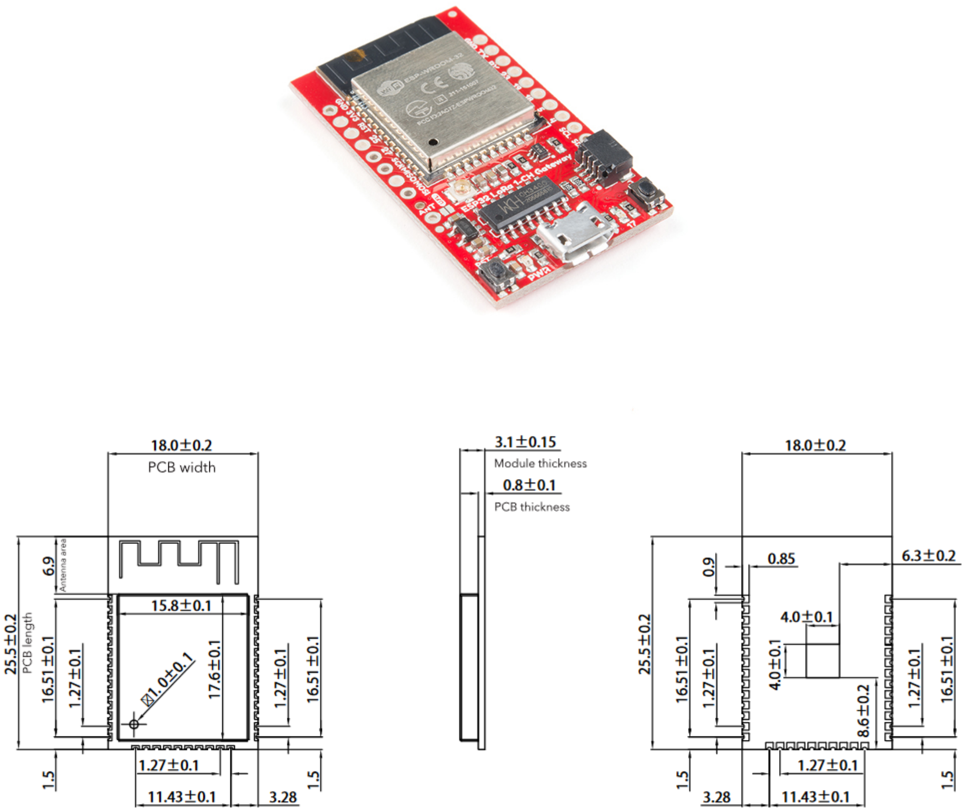

Figure 3.7: From top to bottom: SparkFun LoRa Gateway - 1-Channel (ESP32) WRL-15006 and it's dimensions[14]

The prototype is equipped with a development board featuring the ESP32 micro-controller. This MCU was chosen because using it we are able to test several means of communication with outside systems, two of which that are most interesting for this purpose are Bluetooth Low Energy, henceforth referred to as BLE, and LoRa, a low power radio communication system. Another reason for ESP32 is that we can explore options for reducing the power drain utilizing the MCU's many sleep and hibernation modes, possibly reducing the power requirements of up to 95% or more. The connectivity and interactivity supplied with this board is as follows:

- Standard connectivity and interactivity:
  - WiFi Radio 2.4Ghz IEEE 802.11b/g/n
  - Bluetooth 5.0 and BLE
  - Hope RFM95W LoRa modem 868/915 MHz
  - Micro USB
  - Qwiic [*sic*] connector

  - U.FL connector
- GPIO expanded connectivity:
  - Touch sensor
  - 2x analog-digital converter
  - SPI
  - I^{2}C
- Sensory equipment:
  - Touch sensor
  - Hall effect sensor

3.6 Final prototype

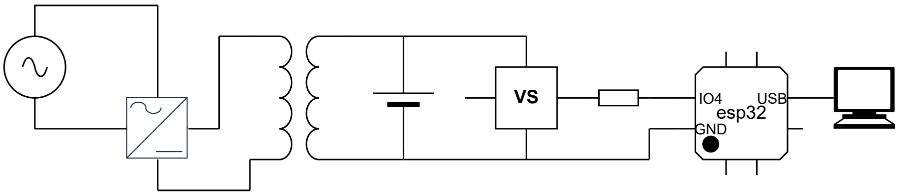

Figure 3.8: Diagram of the testing version of the final prototype

During functionality and power related testing, the components were interconnected to create the final prototype as highlighted in the diagram above. The key difference from the prototype designed for actual deployment was providing the MCU power via a micro USB connection instead of the 3.3V pin in exchange for easy access to internal data via the Arduino IDE's serial monitor.

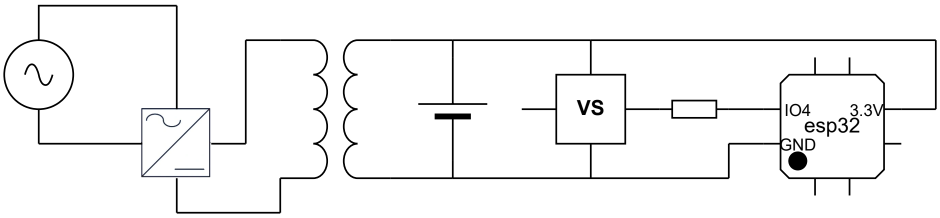

Figure 3.9: Diagram of the deployment version of the prototype

For the actual deployment version as stated above, the USB power connection was replaced by the 3.6V output of the battery into the 3.3V pin, and as such the prototype loses the ability to easily track the internal data flows through the serial monitor. The only way to check if the prototype was reporting correctly would be the BLE output.

Chapter 4

Software implementation

This chapter introduces the software implementation of the expected hardware functionality of the components used in creating the prototype. Starting with the tools used for interfacing with the hardware components 4.1, followed by the overview of the implementation's goals and program structure 4.2, as well as explaining the methods of software developed for on-board signal sampling 4.3 and processing 4.4. The chapter closes with the explanations of methods used for vibration anomaly detection 4.5 and on-board power management 4.6, and communication with other devices 4.7.

4.1 Tools used

The main interface between the code and the MCU is facilitated through the usage of Arduino IDE[3]. This interface is used to compile code written in C++ and flash it onto the MCU. Since ESP32 and Arduino IDE are not out of the box compatible, the ESP32 Arduino Core[6] board manager is being utilized. All inputs and outputs are being tracked and managed through the Arduino IDE serial monitor unless stated otherwise, and analog inputs and outputs are also being verified using the scope multimeter further described in chapter 5, Testing, below.

4.2 Overview and structure

The code used for programming the MCU is divided into two parts. The first part is called the *setup* part of the code, and is only run once on device power up, and subsequently run only in the case of the physical *RST* button being pressed. This part of the code contains the setting of the wake up timer, more on it's function in subsection 6, as well as creation of a BLE client and the setting of the CPU data rate as well as it's clock speed.

4.3 Signal sampling

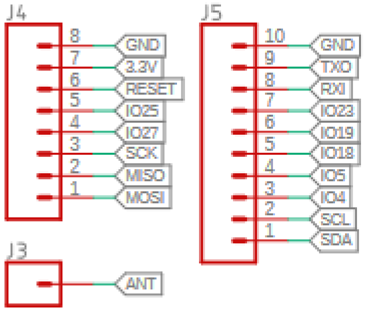

Figure 4.1: SparkFun LoRa Gateway WRL-15006 IO Schematic[5]

In order to record and process the voltage levels inputted into the GPIO 4 pin, which is the only externally accessible pin that gives access to the ESP32's analog-digital converter module[17], we must first sample it at regular intervals. For the ease of conversion and the sake of satisfying the Shannon-Nyquist theorem, as the signal we are processing has a known frequency of 260Hz, we selected a sample rate of one millisecond, or 1000Hz. This allows us to reconstruct a waveform graph in a time domain that serves as a proof of correct function of the analog-digital converter on board the MCU when compared to the scope multi-meter output, and as a proof that we are in fact dealing with an periodic signal. These samples are then saved in an array of values where the index of the value is equal to the exact millisecond from the start of the sample process.

4.4 Signal processing

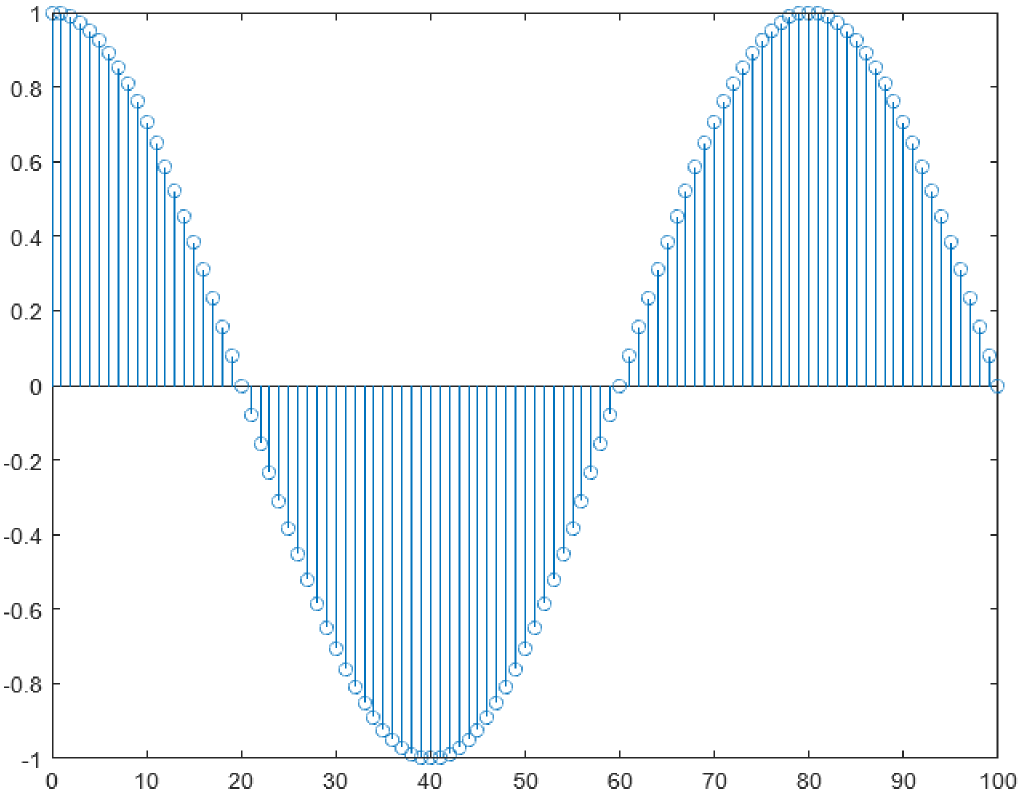

Figure 4.2: Signal sampling illustration

The main goal of signal processing in this thesis is measuring the incoming signal frequency from studying the waveform obtained from sampling said incoming signal for a period of one second. We are working with a presupposition that this signal is produced by cantilever oscillation, and therefore is shaped like a sine wave. This means that if we detect a rising signal edge with a voltage value above average, and then a falling edge with a voltage value below the average voltage value, by subtracting the falling edge index from the rising edge index we gain one half of the signal period. This is possible because the index of the value equals the time at which the value occurred in milliseconds. Then we simply multiply the period by two and convert the time period into signal frequency.

4.5 Anomaly detection

One of the most important goals of this thesis is the ability to detect anomalies in the vibration frequencies of the object of interest. There are many ways of going about this, for example making a structure with identifiers and timers for specific occurrences of frequencies, however since the testing was going to be performed on an object that has a constant frequency, it only necessitated simple comparison after calculating the frequency detected by the MCU. Once the discrepancy has been detected, the code will then send a warning message via the communication method of choice, in this case Bluetooth Low Energy.

4.6 Power management

To reduce the power consumption between scanning cycles, after the measurement of the vibration is taken and the duty cycle is calculated, the device enters a variable duration sleep mode. This variable duration depends entirely on the eventual product customer's needs, usually determined by the safety requirements of the machine being monitored. In the experiment the cycle was set to 1 second vibration polling, followed by a few microseconds of calculations, and finally the cycle ends with a 5 second light sleep. Light sleep can theoretically cut down power consumption by up to 99% when completely idle.

4.7 Inter-device communication

For alert communications between devices, BLE was chosen as the premier low power communications solution. It has considerably less range than traditional Bluetooth, however since a BLE device spends most of it's time in a sleep state, it reduces the power requirements to very low levels. While the power draw is the biggest factor in choosing the method of communications, we can safely ignore the range restrictions as the sensor hub should not be located more than few meters from any of the sensor nodes, or the nodes can utilize a more easily powered outside data transfer node which utilizes full power Bluetooth.

Chapter 5

Testing

This chapter presents the results of testing to asses and affirm the proper functionality of each component of the sensor node and subsequent testing of the two separate subsystem to asses the functionality of the system as a whole.First, it outlines the tools used for the tests' verification 5.1, and then describes the testing procedures. The testing of the components includes the test of whether the energy harvester is not faulty, i.e. it's capability of generating charge at all 5.3, and then assessing how much charge it's capable of generating during specific testing scenarios 5.5. The testing of the sensor includes measuring vibration of an object with a frequency already known to us through it's specifications 5.2, and subsequent usage of the sensor in determining the vibration frequency of the objects using in testing the harvester whose frequency is unable to be determined from credible sources. Final hardware tests include functionality testing of the MCU hardware capabilities 5.4 as well as it's software implementation. The chapter concludes with system power drain comparisons 5.6 and the prototype's viability estimate 5.7.

5.1 Testing equipment

Figure 5.1: UNI-T UT81B Scope Digital Multi-meter[15]

For accurate measurement of output voltage, current and the component's duty cycles, the faculty has provided a UNI-T UT81B model scope digital multi-meter. This device is capable of measuring voltage as low as a tenth of a volt and measuring the current as low as 1 μA. This device will be referred to as „multi-meter“ from this point onward. After testing for accuracy highlighted in chapter 5.2, the Kemet VS-JV10A vibration sensor, referred to only as „sensor“ from this point onward, will also be used as testing equipment, capable of measuring frequencies from 10 to 15000 hertz.

5.2 Assessment of functionality of the vibration sensor

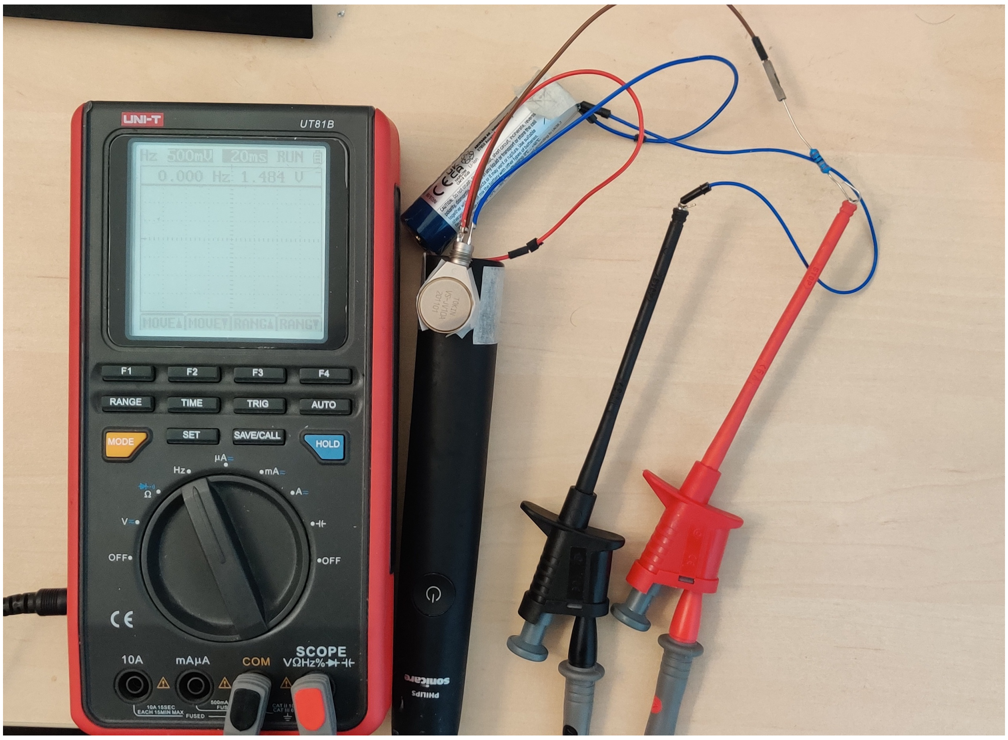

Figure 5.2: Vibration sensor functionality assessment

The vibration sensor unit was tested for accuracy by using it to measure a Philips Sonicare electrically powered vibration toothbrush in the absence of other viable sources of vibration with known parameters. The toothbrush's specified frequency on the „clean“ setting is approximately 260 Hertz. The sensor was attached to the tail end of the toothbrush using duct tape attached to it's sides as the user manual states that continuous pressure to the top face of the sensor might lead to inaccuracies in measurement. The pin designated number 3 was first attached to the negative terminal of the power supply, then the pin designated number 1 was attached to the positive terminal of the power source. Finally, the pin designated number 2, the sensor output, was attached to the positive lead of the multi-meter through a user guide recommended load resistance of 100 kΩ and the negative lead of the multi-meter was attached to common ground with the pin 3 at the negative terminal of the power supply. The voltage indicated at the sensor output was 1.5 volts, which was expected as the manufacturer states that the recommended offset voltage to be used at the output terminal is approximately one half of the power source voltage, i.e. approximately 1.8 volts. The toothbrush was then turned on and the multi-meter set to test the sensor's duty cycle. The duty cycle measured approximately 260 Hertz with the maximum error of +-10 hertz, though this might have been caused by either dampening in the internal construction of the handle or the nature of the construction of the brush where the intended vibration is directed at the head of the brush as opposed to it's tail end, however the brush head had no structurally acceptable attachment point, as it was too small. In conclusion we can surmise that the sensor is working as expected, and is fit to provide measurement data for vibrating objects which had a previously unknown vibration frequency, and this data will be used as a testing reference from this point onward.

5.3 Assessment of functionality of the energy harvester

5.3.1 Preliminary testing and functionality affirmation

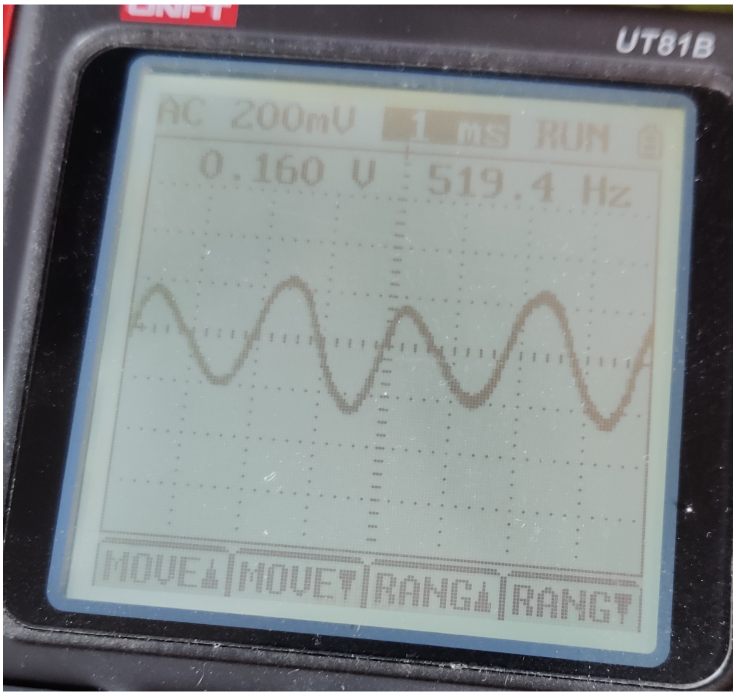

Figure 5.3: Harvester functionality affirmation/charge generation testing

The energy harvester was tested to assess it's functionality by attaching the leads of a multimeter to the harvester's terminals and attaching the harvester to several vibration capable objects objects available at the time of writing this thesis, activating said objects, and then measuring the output current. The harvester successfully created an output current, and as such affirmed that at least at first glance the component was working as intended and has managed to generate charge. Based on this observation it was decided the component could be subjected to more elaborate testing.

Output testing

The harvester has been tested using multiple vibration capable objects in order to attempt to gather enough data so that it would be possible to use the observed output against the combined drain of the device components. This information would then be used to draw a conclusion outlining the number of energy harvesters needed to power the device indefinitely. The objects are going to be sorted first into two categories:

- harvestable devices,
- unharvestable devices.

The thesis will first outline the devices that failed to generate output through the harvester with short remarks on the probable cause, and then will feature a more in-depth look into devices that were successful in enabling the harvester, with detailed testing process descriptions as well as featuring the recorded data.

5.3.2 Unharvestable devices

Devices that failed to produce satisfactory results are as follows:

Small tower speakers 20x20x60cm - unharvestable, probable cause - speakers are built to suppress the vibration from the inner magnetic coil to avoid causing reverberations compromising sound quality.

Large tower speakers 40x50x120cm - unharvestable, probable cause - same as highlighted above, worth nothing is that even music that heavily emphasized bass at high loudness failed to transfer through the speaker frame

Washing machine - unharvestable, actually produced output when in full centrifugal mode, however considering the comparatively low amount of time modern machines spend in this state the power output would be very inconsistent.

5.3.3 Harvestable devices

This subsection will highlight the precise testing conditions and results gathered from aforementioned tests with devices that did produce noteworthy results.

Vibration toothbrush

After using the vibration toothbrush as a reference point for testing the accuracy of the vibration sensor, it was also used in measuring the output of the energy harvester itself. The harvester was attached with duct tape to the tail end of the toothbrush for the same reasons highlighted in testing the sensor in chapter 3 section 1. The brush was then activated on the clean setting and multi-meter was set to first measure the output voltage, and then switched modes to measure current. It is worth noting that as highlighted in chapter 3 section 1, the harvester did in fact produce alternating current, proving the necessity of a full wave rectifier in order to harvest the charge generation from both halves of the cantilever beam deflection period.

Electric epilator

The second power output test used an electric skin hair remover which had an internal electrical motor which caused the object's chassis to vibrate. This vibration emanated at a consistent enough frequency and amplitude to produce power output in the harvester component when taped to the center of the chassis.

Figure 5.4: Philips DiamondClean Sonic Toothbrush[11]

Electric lawnmower

The final power output test used a lawnmower powered by an electric motor. This motor was much more powerful than either the toothbrush or the hair remover, however it caused the top part of the chassis to vibrate at a lower frequency than the previous two tests, albeit at a higher amplitude.

5.4 Assessment of functionality of the MCU

5.4.1 Power systems

Because of the MCU's ability to be powered by many different means it was deemed prudent to perform several tests to see if the means that are relevant to this thesis are functioning to a satisfactory level.

Since it is necessary to flash the MCU with code containing the relevant instructions, it needs to be able to be powered and have data transferred into it via the micro USB port located at the bottom side of the board. The board was plugged into a standard laptop USB-A slot and both the data transfer and power input systems' performance was deemed satisfactory after several tests involving flashing new pieces of code and subsequent flashing and rebooting of the board.

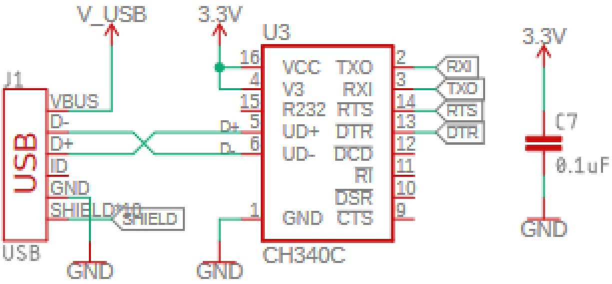

Figure 5.5: esp32 USB connection schematic[5]

5.4.2 Analog-digital converter

Unfortunately only the second ADC unit was prone to testing as the esp32 board used in testing the prototype only had one ADC pin available for outside access. First, the bit width was set to 12 bits for the best possible resolution after which several tests using multiple input devices were performed.

Standard battery

A battery which is used as an energy storage for this prototype was connected to the ADC pins, and the ADC successfully detected a voltage level of 3.56 volts after conversion from ADC output.

Vibration sensor

First the sensor data output was connected without any vibrating equipment attached. The ADC successfully detected the reference voltage of 1.78 volts.

For the second test the sensor was attached to the aforementioned vibration toothbrush which continues to serve as a vibration reference point. The ADC correctly produced a range of one thousand voltage values which strongly implied a sine wave progression. After applying the algorithm highlighted in chapter 4, the program calculated a vibration frequency of 250Hz, which accounting for the compound error caused by ADC module sensitivity, sampling , signal reconstruction and the crudeness of the frequency calculation method is satisfactory as the true frequency reported by the the vibration sensor linked to a scope multimeter was 258Hz +- 1Hz.

5.4.3 Bluetooth low energy

Bluetooth low energy testing was performed using an example data read server application. This application advertises data, in this case a dummy frequency report. The server was then connected to with a BLE scanner Android smartphone application and the dummy report was successfully retrieved.

5.5 Harvester power output data comparison

The below table contains compiled results from testing performed and highlighted in subsection 2.

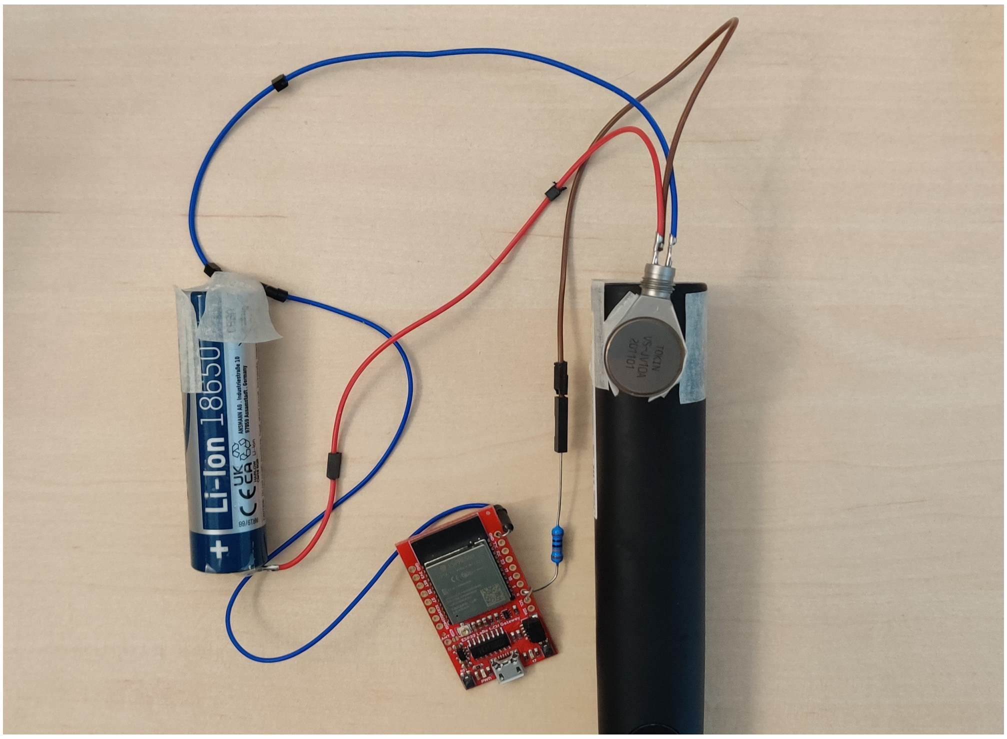

Figure 5.6: MCU analog-digital converter input testing and frequency calculation setup (USB to PC connection omitted)

Harvester power output		
Test Device	Voltage	Current
Vibration Toothbrush	160 mV	10 µA
Electric Epilator	112 mV	7.6 µA
Electric Lawnmower	0.3 mV	4 µA

5.6 MCU power drain testing

Power drain testing was performed by cutting into a micro USB cable and cutting the power line and subsequently injecting the scope multimeter's power leads to mend the circuit while getting accurate power consumption reports. The below table illustrates the energy drain of all the relevant tests mentioned above.

Energy Drain Testing		
Test Type	Power Drain	Is Constant
Idle Light Sleep	6.8 mA	Yes
Signal Sampling	32.9 mA	No (1 s burst)
Duty Cycle Calc.	50 mA	No (1 ms burst)
BLE Read Server	60 mA	No (20 ms burst)
Total Avg. (BLE Read)	11 mA	Yes

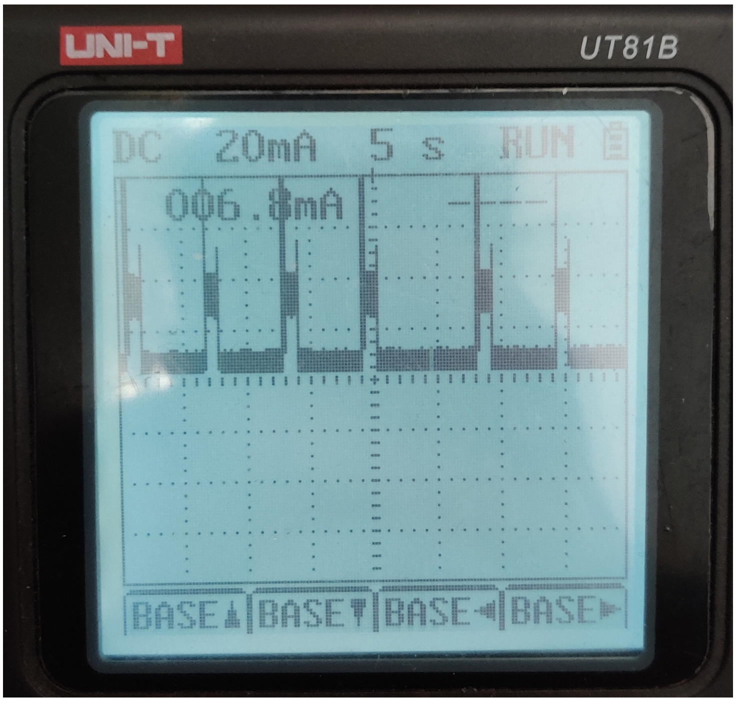

Figure 5.7: Signal sampling and frequency calculation power drain cycle

5.7 Feasibility evaluation

The main problem when dealing with feasibility of implementation in a real scenario when it comes to energy harvesting powered appliances is how many harvesters it takes to perpetually power the rest of the circuit. As highlighted in subsection 4, the biggest power output was achieved by testing the harvester with the vibration toothbrush, managing the combined output of 1.6 μW.

Using data highlighted from subsection 5, and presupposing that we could synchronize the BLE connection and packet sending between devices to take 20 ms, and the rest of the functions behave similarly to the behaviour highlighted in the testing chapter, ergo 5 s light sleep, 1 ms calculation, 1 s signal sampling, the average power consumption would equal to 7 mW, vibration sensor included, it's ability to recycle charge excluded. To satisfy these power requirements of this cycle permanently, we would need to employ, counting in the efficiencies of AC/DC power conversion and voltage up scaling, 50 groups of 27 harvesters in a series each producing 42 μW, in parallel, to remove the need for the voltage up scaling, as each group produces the 4.2 V needed to peak charge the battery, or 7000 individual harvesters in parallel, over current notwithstanding.

This particular prototype would end up costing upwards of 75000 dollars per sensor node. This prohibitively high cost limits the usability of this node network for monitoring all but the most expensive machinery and construction, unless a different more efficient cost to energy produced harvester components were to be used, or significant power efficiency tweaks in the MCU programming were to be achieved, such as exploiting esp32's ultra low power co-processor while keeping the main CPU under permanent hibernation or deep sleep modes.

Chapter 6

Conclusion

This thesis explores the options of protection of machinery and construction by detecting anomalous vibration frequencies while exploiting them to self power the sensory equipment. It's primary challenges were evaluating industrial use of a self powered frequency sensing and warning signal sending circuit using frequency detection achieved by sampling and processing analog voltage input while minimizing component power drain.

To satisfy the postulated prototype's functional requirements, a sensor was hand picked capable of sensing a wide frequency band of vibrations. Using the voltage output of this sensor we were able to very closely approximate the vibration's frequency. With this information, we can safely decide whether this vibration is within the safe operating specifications of the observed object. To allow this sensor to be placed in hard to reach or completely impossible places, components for self-power-ability and wireless communications with the outside world were considered and integrated. Finally, the cost and performance of these components were evaluated, and deployment feasibility was considered.

The main benefits from this thesis are the complete theoretical circuit design of the prototype self powered warning system, extensive testing of functionality of every component in the circuit and methods of interfacing between them, design of an algorithm for approximating a vibration frequency from analog voltage input, it's ability to be deployed at any vibration source for monitoring, even with restricted access after deployment, and the prototype's feasibility evaluation of it's ability to be deployed in the current industry environment.

The most notable points of improvement considering further research and development of this thesis' topic are extensive testing of more options for energy harvesting such as pyroelectricity, wind or magnetic power on a micro scale as well as further performance testing of different models of piezoelectric energy harvesters, exploring methods of recycling power input to the sensor, owing to it's design also including a bending transducer, and exploiting esp32's ultra low power co-processor as well as permanently powering down as many of it's subsystems as possible in order to further reduce the power drain of the circuit and drive down the overall cost of the prototype, making it more affordable to deploy.

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Appendix A

Contents of the physical medium

```
/
├── src/
├── text/
├── xgajdo18_thesis.pdf
├── requirements.txt
└── README.txt
```

src/ contains the source code for the MCU programming

text/ contains the source code for compiling the thesis PDF

xgajdo18_thesis.pdf contains the thesis text in PDF format

requirements.txt contains the software requirements for running the code on the MCU

README.txt additional information on how to run the project code and how to replicate testing conditions