Department of Electronic and Telecommunication Engineering
University of Moratuwa

Design Methodology

Industrial Machine Vibration Monitoring System

EN2160: Electronic Design Realization

Index Number	**Name**
210542B	R.M.L.H. Ratnayake
210549D	N.P.S.S. Rupasinghe

Group K (30)

Contents

Abbreviations

Abbreviation	Definition
MCU	Micro Controller Unit
IMU	Inertial Measurement Unit
PCB	Printed Circuit Board
3D	3 - dimensional
ML	Machine Learning
AI	Artificial Intelligence
I2C	Inter-Integrated Circuits (I^2C)
GUI	Graphical User Interface
PC	Personal Computer
IoT	Internet of Things
CAN	Controller Area Network
MQTT	Message Queuing Telemetry Transport
IC	Integrated Circuit
UART	Universal Asynchronous Receiver-Transmitter

Chapter 1

Review Progress

With both our day-to-day experience and special observations before the commencement of this project, we noticed that many industries use large-scale machines and parts such as motors, that vibrate in their general operation. However, most of the time, these machines run for a prolonged time without any inspection and can cause sudden failures, putting the entire flow of the factory/ industry/ company at a halt. If we could monitor the behavior of the machine continuously, we might have the chance to identify potential failures and malfunctions sometime before they happen, sometimes days, weeks, or even months in advance.

To address this issue there are some existing monitoring devices and techniques used in the industry. However, in this project, what we targeted was developing our own method for monitoring and identifying failures in industrial machines by analyzing the anomalies in their vibrations.

First, we did research on what are the existing solutions, and their working principles of them. Then, we studied the physics of vibrations to get a better idea about the scope of our interest. After that, we came up with an initial idea on how to address this issue. There, we identified the components we would need, some design methodologies, and the stakeholders of the project. Other than that, we extended our background research considering the aspects we had already learned, such as applying Fourier techniques to analyze signals in the frequency domain, consideration of Nyquist's Theorem when sampling signals, etc.

After these preliminary steps, we found the components needed and tested them both individually and as a whole or a combination of various components. During this time, we came up with several conceptual designs on how to design the prototype. After careful evaluation of the various possibilities along with their pros and cons, we adhered to one design. Then, we continued developing the product meeting the requirements and targets we identified particular to the selected design.

The design mainly consisted of two units: one main unit connected to a PC for analysis and a secondary unit containing the accelerometer sensor to be connected to the machine part. The PC runs custom-designed software that can collect data from the device and analyze them, plot graphically, and indicate anomalies. The software design was started mainly using Python, since that made it easy to combine the different software parts like the machine learning model, and the GUI application, along with the libraries for handling communication with the device. Concurrently, firmware development for the device was started using C++.

Once the basic stuff is in order, and the conceptual design is finalized, PCB designing, and enclosure designing were begun. The finalized schematic designs adhering to professional techniques like hierarchical design, were used to design the PCBs. We designed two PCBs: one for the main device, and a second PCB for the sensor, with extensions to daisy-chain multiple sensors, that can be fixed on different places of the target machine for increased accuracy in analysis and predictions.

We approached a PCB-enclosure co-design method to reduce time wastage and better interconnection between the two aspects. While one of the group members was designing the PCBs, the other one started designing the enclosures for the two device parts. This was also done carefully adhering to professional software and techniques.

Once the PCB design and enclosure design were finalized, the PCBs were sent to be fabricated and the enclosures to be 3D printed. Meanwhile, the selected components were ordered from international vendors.

While we were waiting for the PCBs, components, and enclosures, we continued developing the software for the product. We developed a machine learning model to detect anomalies of the vibrations. Then we integrated it with the GUI application we developed, which was originally developed to make the user experience better and with the idea to develop a complete package of products during this project.

Moreover, we documented all those steps and progress of each individual day, both as manual documents, especially for the design decisions, PCB and enclosure designs, etc., and as commits in Git version control, especially for the software development.

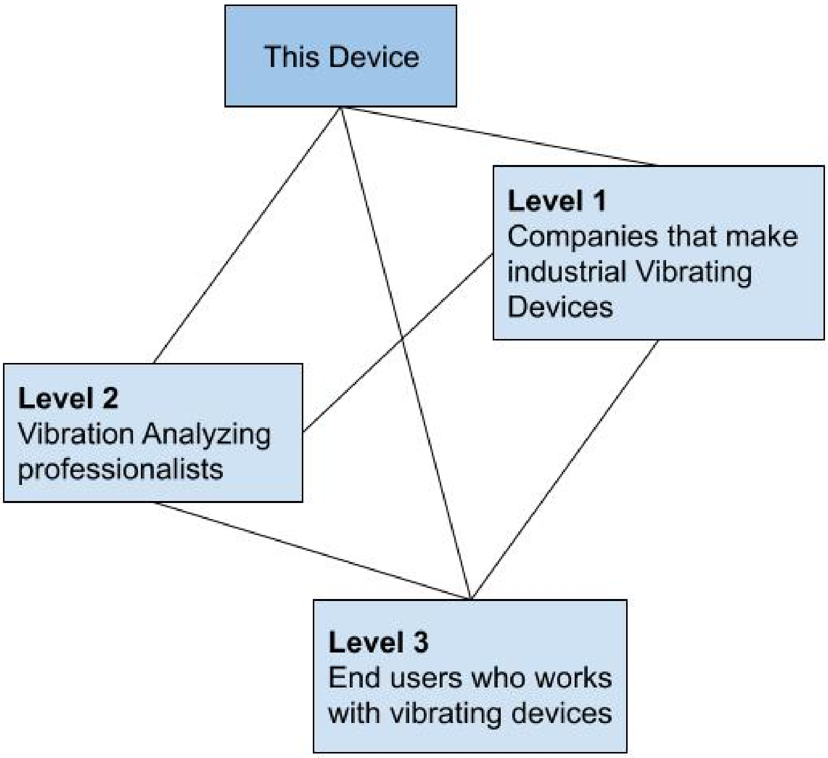
Once everything arrived, we soldered the components to the PCBs and tested the operation. The PCBs appeared to be working as expected. So, then we burnt the bootloader to the microcontroller we chose, ATmega328P, and uploaded the developed firmware. Then we tested the communication of the device with the PC, and it worked as expected.

So, overall, all the parts regarding an industrial-level product development are completed in this project, such as identifying user requirements, stakeholders, background research, developing schematic, PCBs, proper enclosures for the product, and even a GUI application for the user to easily interact with the device

Chapter 2

Stake Holders and User Observation

In the industry, some devices are meant to vibrate or rotate and some devices are made such that they should not vibrate. Any of these devices can have vibration anomalies.



The stakeholders of our device include Companies and individuals. The connection between those stakeholders is shown above. We recognized stakeholders on 3 levels.

2.1 Level 1 - Companies

Some companies provide monitoring/ debugging devices specific to their industrial vibrating machines, but not for the end user and only for specialists. Some manufacturers do not provide any tools at all.

They will be interested in our product because the only thing they have to do is train our Machine-learning model with their data set and give it to the end users or vibration-analyzing technicians.

1. SKF Description: SKF offers a wide range of vibration monitoring products, including accelerometers, vibration sensors, and portable vibration meters. These devices are designed to measure and monitor vibration levels in industrial machinery. However, SKF typically does not provide standalone analysis or diagnostic software. Users may need to utilize third-party software solutions for in-depth analysis.
   Website: SKF

2. IMI Sensors Description: IMI Sensors specializes in manufacturing industrial vibration monitoring products such as accelerometers, vibration switches, and signal conditioners. Their sensors are widely used for monitoring rotating machinery and equipment. However, IMI Sensors primarily focus on providing hardware solutions rather than analysis tools.
   Website: IMI Sensors

3. Dytran Instruments Description: Dytran Instruments manufactures a variety of vibration measurement sensors, including accelerometers and vibration meters, for industrial and aerospace applications. While their sensors are designed to capture vibration data accurately, Dytran only typically offers dedicated software for analyzing or processing the collected data.
   Website: Dytran Instruments

4. Metrix Instrument Co. Description: Metrix Instrument Co. produces vibration monitoring products such as vibration transmitters, proximity probes, and seismic sensors for industrial applications. Their sensors are commonly used for condition monitoring. However, Metrix Instrument Co. does not provide specialized software for analyzing vibration data.
   Website: Metrix Instrument Co.

5. Columbia Research Laboratories, Inc. Description: Columbia Research Laboratories manufactures vibration monitoring equipment, including accelerometers and vibration switches, for industrial and aerospace applications. Their sensors are designed to capture vibration data accurately. However, Columbia Research Laboratories typically focuses on providing hardware solutions rather than analysis tools.
   Website: Columbia Research Laboratories, Inc.

2.2 Level 2 - Professionals

Most Vibration analysts use tools to understand the anomalies of mechanical vibration of industrial devices.
There are different varieties of these devices in the market. Some of these tools have built-in monitors so that analysts can view real-time data plots, Others provide apps so that they can view data from those apps. Analysts have to make decisions by their knowledge by looking at the graphs and data sets.

Our device is not designed specifically to suit a particular machine, but a generic device. So, the professionals can use our device with any vibrating device. Using our product, they can make correct decisions with the help of Machine Learning models and the power of AI.

2.3 Level 3 - End Users

Since our product is a general device and not designed for a specific device and our product is ideal for identifying any kind of vibration-related anomalies, end users can use this with any vibrating device.

They can make correct decisions and with those valid decisions, they can call professionals or contact the company that created their device for further decisions.

Chapter 3

User Requirements and Need List

Within the limited domain of stakeholders, there are many functions and qualities that those stakeholders and users expect from such a device.

Expectations regarding an industrial machine:

1. To make sure that their industrial machines work properly.
2. Make sure the safety of the workplace and machines.
3. Make sure the lifetime of the industrial device.
4. Make sure to give a quality end product or good-quality output
5. Reduce maintenance costs by making correct decisions with the guidance of the device.

Expectations regarding an anomaly monitoring device:

1. Ease of use.
2. To make quick decisions.
3. Reachability to the vibrating device.
4. Adaptability to different vibrating devices.

In addition to the specific expectations outlined above, it is essential to recognize that the successful implementation of a vibration monitoring system hinges on its ability to seamlessly integrate into existing workflows. The device should offer intuitive interfaces and user-friendly features to ensure that operators can easily interpret the data and act swiftly on any anomalies detected. Furthermore, the system should be robust and versatile, capable of adapting to a wide range of industrial environments and machinery types.

By meeting these comprehensive user requirements, the vibration monitoring system will not only enhance the operational efficiency and safety of industrial machines but also contribute to prolonged equipment lifespan and reduced maintenance costs, ultimately delivering higher quality outputs and improved overall productivity.

Chapter 4

Similar Products in the Market

1. VibraLink by PRÜFTECHNIK. Description: VibraLink offers comprehensive vibration monitoring solutions with integrated software and hardware sensors. It is designed for real-time condition monitoring and predictive maintenance of industrial machinery.
   Website: PRÜFTECHNIK VibraLink

2. SKF Multilog IMx. Description: SKF Multilog IMx is an advanced monitoring system that provides continuous monitoring of machinery health. It includes a variety of vibration sensors and sophisticated software for data analysis and predictive maintenance.
   Website: SKF Multilog IMx

3. National Instruments (NI) CompactRIO. Description: NI CompactRIO is a rugged, reconfigurable monitoring system that integrates vibration sensors and high-performance software for industrial monitoring and control applications. It is suitable for harsh environments and offers customizable monitoring solutions.
   Website: NI CompactRIO

4. Emerson AMS 6500 ATG. Description: Emerson AMS 6500 ATG provides online machinery health monitoring with advanced vibration analysis and diagnostics. It combines durable hardware sensors with powerful software to ensure the reliability and efficiency of industrial equipment.
   Website: Emerson AMS 6500 ATG

5. Brüel Kjær Vibro (BK Vibro) VIBROCONTROL 6000. Description: VIBROCONTROL 6000 is a versatile vibration monitoring system from Brüel Kjær Vibro that includes sensors and comprehensive software for machine condition monitoring and diagnostics. It supports various industrial applications and ensures proactive maintenance.
   Website: BK Vibro VIBROCONTROL 6000

Chapter 5

Stimulate Ideas

To foster innovative solutions for the industrial machine vibration monitoring system for machines, we employed a variety of idea stimulation techniques. These methods promote creativity, collaboration, and comprehensive exploration of potential solutions.

5.1 Idea Stimulation Techniques Used

Research and Benchmarking

Approach: Extensive research on existing vibration monitoring technologies and benchmarking against industry standards.
Benefits: Identifies current best practices, reveals market gaps, and provides a solid foundation for developing advanced solutions.

Peer Discussion

Approach: Regular discussions with peers and experts to share knowledge, experiences, and insights related to technology use in the project.
Benefits: Promotes knowledge exchange, sparks new ideas, and offers diverse perspectives on potential solutions.

Mind Mapping

Approach: Using mind mapping tools to visually organize thoughts and ideas related to the project.
Benefits: Helps identify connections between different concepts, encourages structured thinking, and facilitates brainstorming sessions.

Brainstorming

Approach: Conducting structured brainstorming sessions to generate a wide range of ideas and solutions for the Vibration Monitoring System.
Benefits: Encourages free-thinking, allows for rapid idea generation, and promotes team collaboration.

Conceptual Design Creation *Approach:* Developing multiple conceptual designs to explore various approaches to the design.
Benefits: Visualizes potential solutions, allows for comparison of different designs, and facilitates the evaluation of their feasibility and effectiveness.

5.2 Steps for Implementing Idea Stimulation Techniques

Conduct Comprehensive Research

Gather extensive information on existing technologies, materials, and methodologies related to the project.

Initiate Discussions

Schedule regular meetings with team members and experts to discuss the project and share insights.

Create Mind Maps

Utilize mind mapping to organize ideas, identify key concepts, and establish relationships between different elements of the project.

Brainstorm Sessions

Host brainstorming sessions where all team members contribute ideas without criticism.

Develop Conceptual Designs

Translate the most promising ideas into conceptual designs. Create sketches and models to visualize each concept.

Evaluate Designs

Assess each conceptual design for feasibility, cost, effectiveness, and potential impact. Select the best ideas for further development.

By integrating these techniques, we ensure a thorough exploration of potential solutions, leading to innovative and effective designs for the industrial machine vibration monitoring system.

Chapter 6

Conceptual Design

6.1 Design Number 1

A single accelerometer sensor is used and is connected to the main processing unit through cables. The sensor part is designed to properly attach to a device/ machine. The collected data will be occasionally sent to a computer with or without user interaction to process. There the anomalies will be identified and notified to the respective authorities.

6.1.1 Basic Architecture

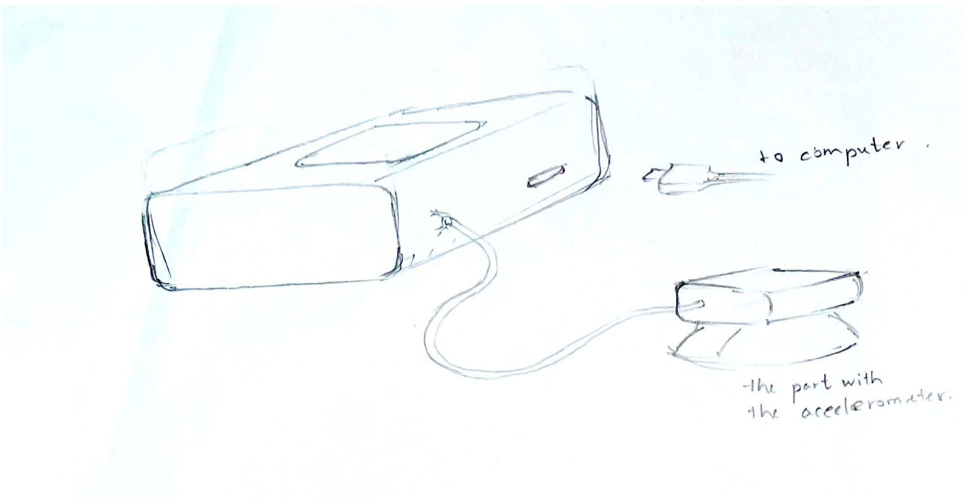


Figure 6.1: Architecture 1

6.1.2 Functional Block Diagram

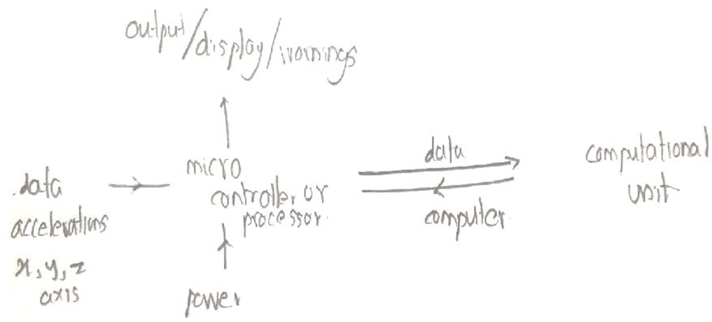


Figure 6.2: Block Diagram 1

6.2 Design Number 2

In this design, multiple sensors are implemented in different locations of the device/ machine where we plan to measure vibrations. With this approach, we can collect more data thus increasing the accuracy of the predictions. However, those sensors will be battery-powered and connected to the main controller through wireless connectivity. The microcontroller is connected to the data processing element and will indicate and provide warnings depending on the feedback from the data processing. There is the possibility to customize the way that the multiple sensors are connected. This enables easy installation, modification, and removal of the sensors.

6.2.1 Basic Architecture

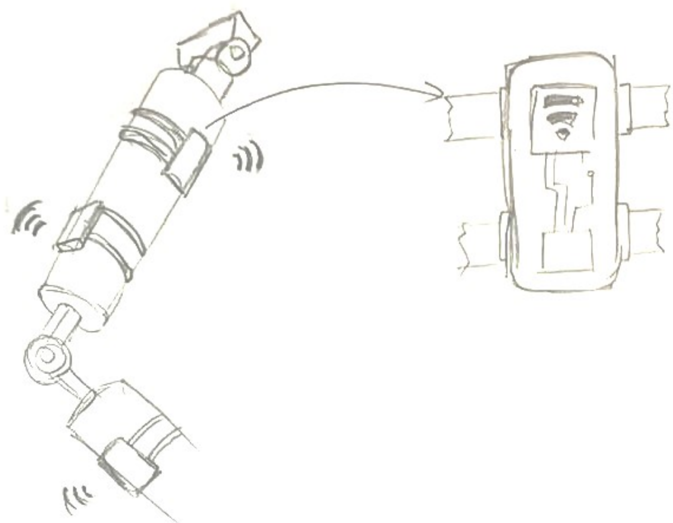


Figure 6.3: Architecture 2

6.2.2 Functional Block Diagram

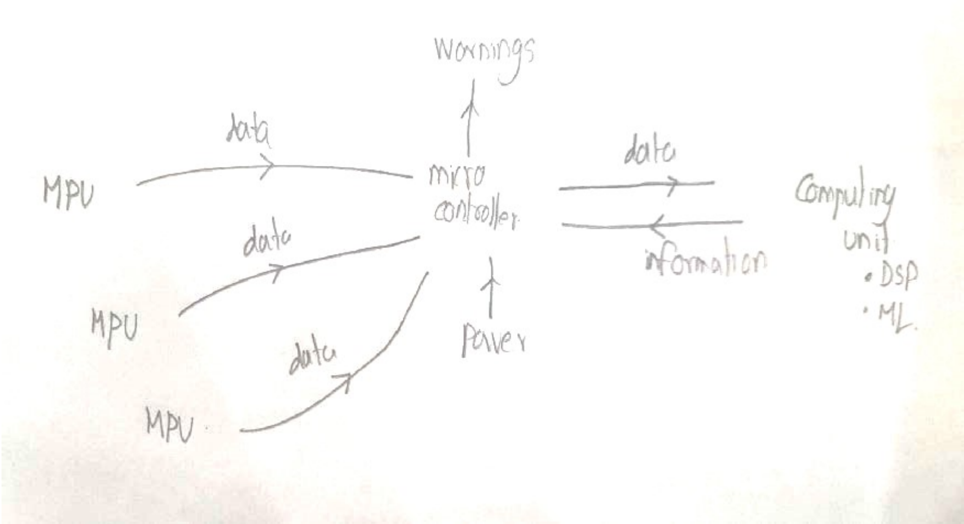


Figure 6.4: Block Diagram 2 - 1

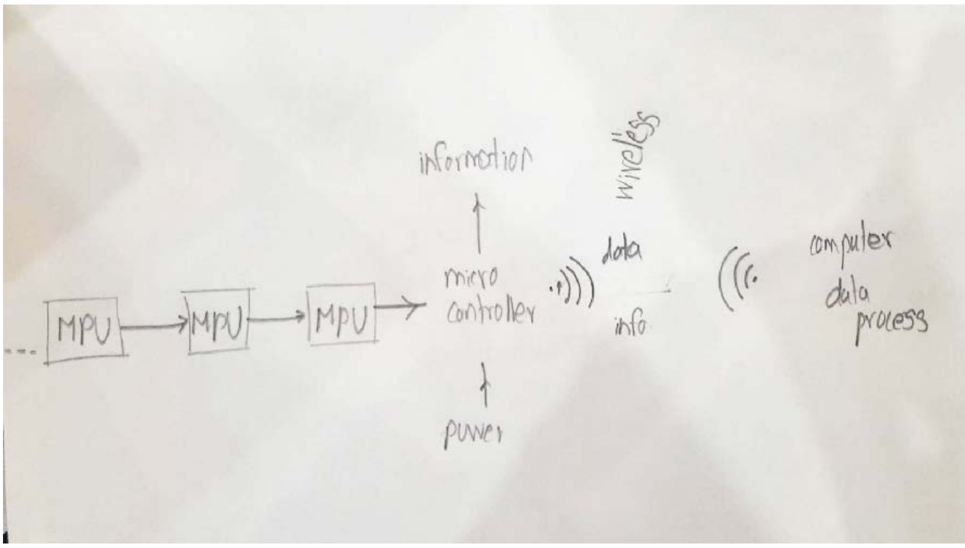


Figure 6.5: Block Diagram 2 - 2

There is the possibility to customize the way that the multiple sensors are connected. This enables easy installation, modification, and removal of the sensors.

6.3 Design Number 3

The data from the single accelerometer is collected and sent to the Cloud. Then that data is accessed and analyzed in a remote location.

6.3.1 Basic Architecture

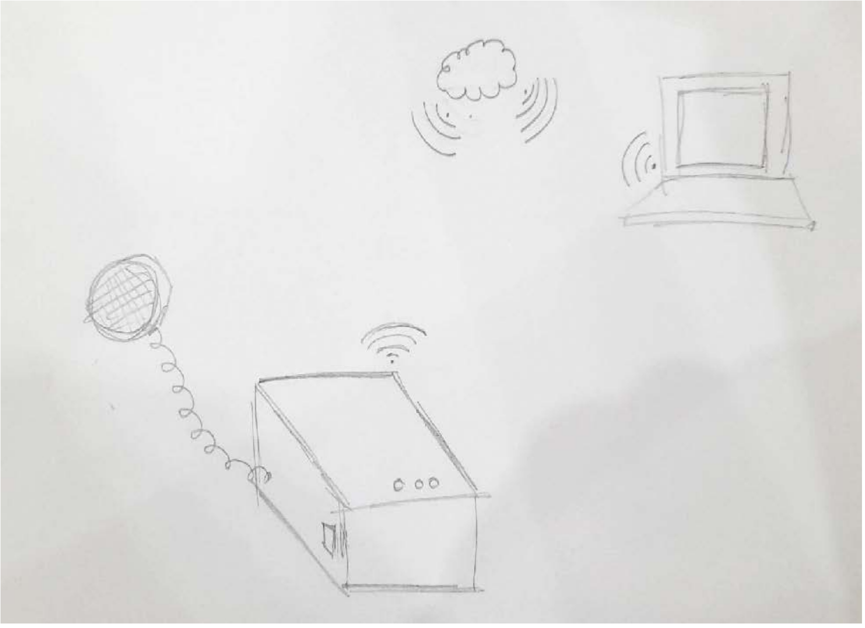


Figure 6.6: Architecture 3

6.3.2 Functional Block Diagram

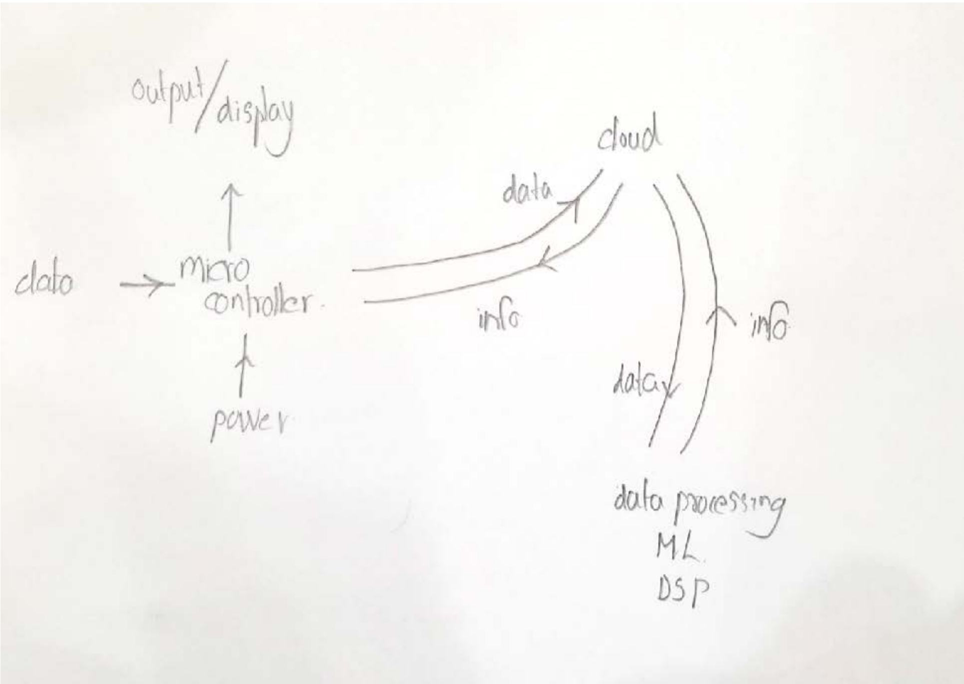


Figure 6.7: Block Diagram 3

6.4 Design Number 4

Multiple sensors are connected to the main part through wired connections and then the main part is connected to the PC to analyze the collected data.

6.4.1 Basic Architecture

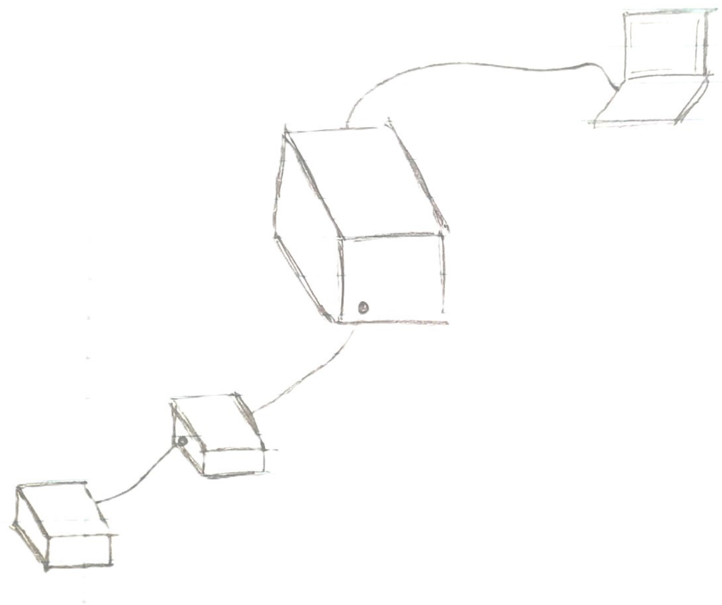


Figure 6.8: Architecture 4

6.4.2 Functional Block Diagram

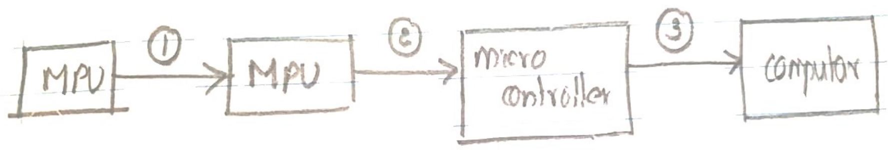


Figure 6.9: Block Diagram 4

6.5 Evaluation of the Design

6.5.1 Criteria for Basic Architecture

1. Functionality: How well does the design support the main functionalities?
2. Aesthetics: How much eye-catching and overall appeal of the user have?
3. Heat dissipation: How much heat is generated and how well has it been managed?
4. Assembly and serviceability: How easily is the assembly and disassembly done?
5. Ergonomics: How well does the design 1t in the user's hand allow easy interaction?
6. Durability: How well does the design withstand impacts and environmental conditions?
7. Simplicity

6.5.2 Criteria for Functional Block Diagram

1. Functionality: How well does the circuit design meet functional requirements?
2. User experience: How intuitive and user-friendly is the interaction?
3. Manufacturing feasibility: Evaluate the feasibility of manufacturing the design
4. Cost: Evaluate the overall cost-effectiveness of the provided functionality
5. Performance: Evaluate the signal quality, resolution, and bandwidth range.
6. Future proofing: To what extent does the design allow for easy replacement or upgrade of individual components?
7. Power Efficiency: How effectively does the device manage power consumption?

6.6 Complete Comparison

		Design 1	**Design 2**	**Design 3**	**Design 4**
Newly added features		Wired connection to the main device. Wired connection to a computer. Specialized mechanism to attach.	Multiple accelerometers to get data from multiple locations of the device/ machine. Wireless connectivity from accelerometers to central control.	Data is sent to the Cloud.	Wired connections between sensors and the PC. Indicator LEDs.
Removed features			Wired connections.	Multiple accelerometers are removed and only one is left.	Wireless connectivity.
Enclosure design criteria comparison	Functionality	8	9	8	9
	Aesthetics	7	7	9	8
	Structural integrity	8	8	8	8
	Assembly and serviceability	9	7	8	8
	Ergonomics	8	9	9	8
	Simplicity	9	7	8	9
	Durability	8	7	8	9
Functional block design criteria comparison	Functionality	7	8	8	8
	User experience	6	8	10	8
	Manufacturing feasibility	9	8	8	8
	Cost	8	7	7	8
	Performance	7	10	9	10
	Future-proofing	6	9	8	9
	Power	8	8	8	8
Total		**109**	**112**	**116**	**118**

Table 6.1: Comparison of the Conceptual Designs

Chapter 7

All Our Approaches

7.1 For Functional Block Diagrams

For data collection, Machine Learning (ML), and User Interface (UI) we first came up with fully cloud-based architecture with Microsoft Azure platforms.

with that, we had the chance to develop our project as an Internet of Things (IoT) based project with ESP32 microcontroller, and protocols like MQTT protocol for IoT.
The obstacles that we faced were,

1. Soldering issues related to ESP32, however, if it was soldered, with a very big sampling frequency collecting sampled data and transmitting them through wifi requires big computational power.

2. We have to make a dedicated power supply for the device. With a power-hungry microcontroller, providing power for a long time is a big challenge.

7.2 For Modular Architecture

For the modular architecture, our initial plan was to use CAN Bus and its protocols. we used Arduino with CAN bus shields and it was successful but we faced a few difficulties

with the limitation of time and complexity of the PCB, we used the I2C protocol which is built into ATmega chips. Also, it has limitations

1. Only 2 IMUs at a time can be connected to the device.

2. Since this is wired, and designed mainly for inter-PCB communication we cannot establish good communication between devices if the connected wire is too long

Chapter 8

Selected Design

As mentioned above in Chapter 5 with all the constraints, limitations, and possibilities, while considering reliability and accuracy we came up with the final Design - Conceptual Design 4. It is based on **Fully wired** and **Semi-modular** design and architecture.

Because of the modular architecture, one IMU will connect to another IMU in a modular fashion and they will communicate with the main controller with I2C communication protocol. The main controller will connect to the Computer using USB communication.

Data will flow from IMUs to the main controller and from then to the computer. All the data processing will be done on the computer.

Detailed descriptions of how data is collected, data flows in the system, and details about computations with different levels of details will be available in

Design Methodology (this document) - 7.1 Flow diagrams
Comprehensive Design - Chapter 2, Chapter 3, Chapter 4

Chapter 9

Preliminary Design

We chose MPU6050 as the Inertial Measurement Unit (IMU) sensor and ATmega328P-AU as the Microcontroller unit (MCU)

9.1 Flow diagrams

9.1.1 Data flow in devices

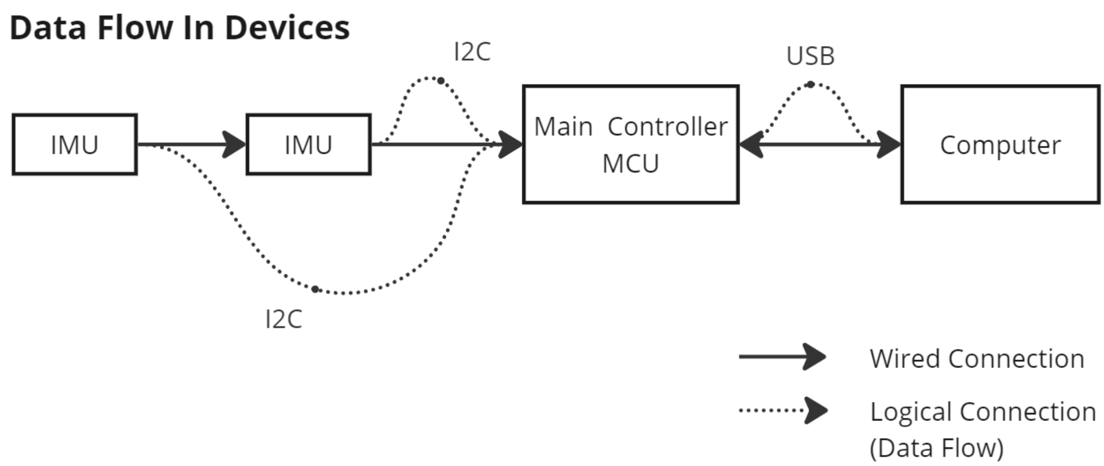


Figure 9.1: Data Flow in Devices

The system consists of three main components, IMU sensors, the MCU, and the computer.

The microcontroller controls data collection with a pre-determined frequency. It can connect to multiple IMU sensors at once through the I2C protocol. Once the MCU accumulates a pre-determined number of data points in its internal buffer, it sends them to the computer through UART protocol.

Within the same PCB where the microcontroller ATmega328P is placed, there is an FTDI FT232RL UART-to-USB converter IC which converts the incoming UART data to USB.

The data is then processed by the custom software running on the computer using Machine Learning capabilities. If anomalies are detected it sends a signal back to the MCU to give indications to the user, such as lighting up an LED.

As it is depicted in the above diagram, all the components are connected through wired media.

9.1.2 Data Flow in ML model

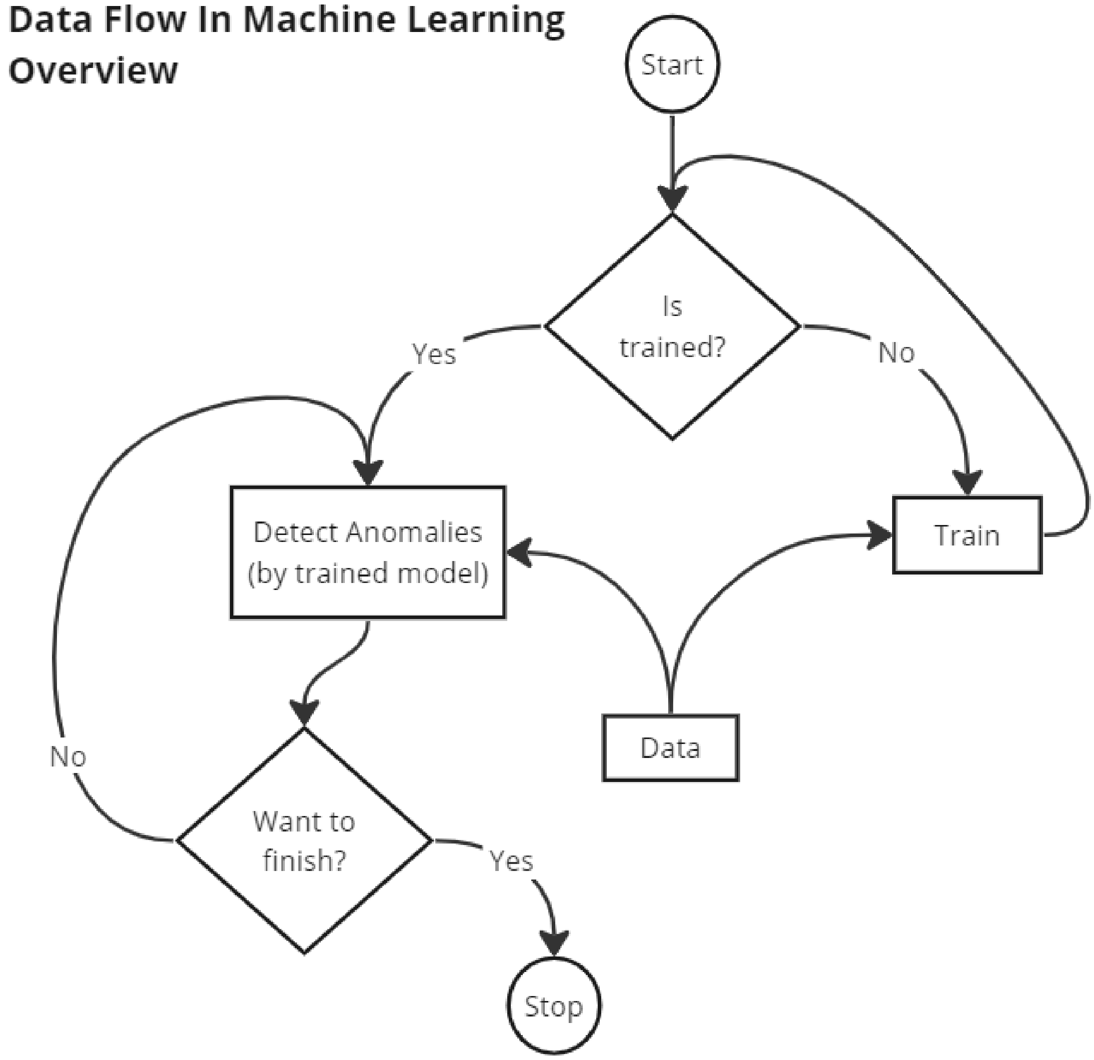


Figure 9.2: Data Flow in Machine Learning Model

The software running on the computer uses **three separate copies** of the same ML model for the three axes of the accelerometer, of which the data is collected and sent separately by the MCU.

In each of those identical models, the incoming data of the particular axis are used for predicting anomalies. First, if the models are not trained, they need to be trained with data which are collected over some time.

Then, as the main operation of the software, Machine Learning models predict anomalies of new data upon arrival to the software. This is a real-time process determined by the pre-set sampling frequency, and the buffer size (how many samples are collected and sent as batches).

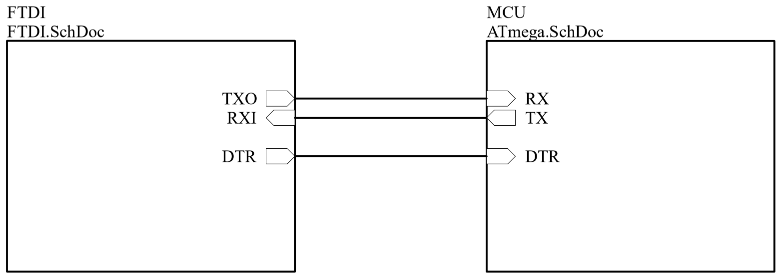
This operation continues until the user stops the program.

9.2 Schematic And PCB

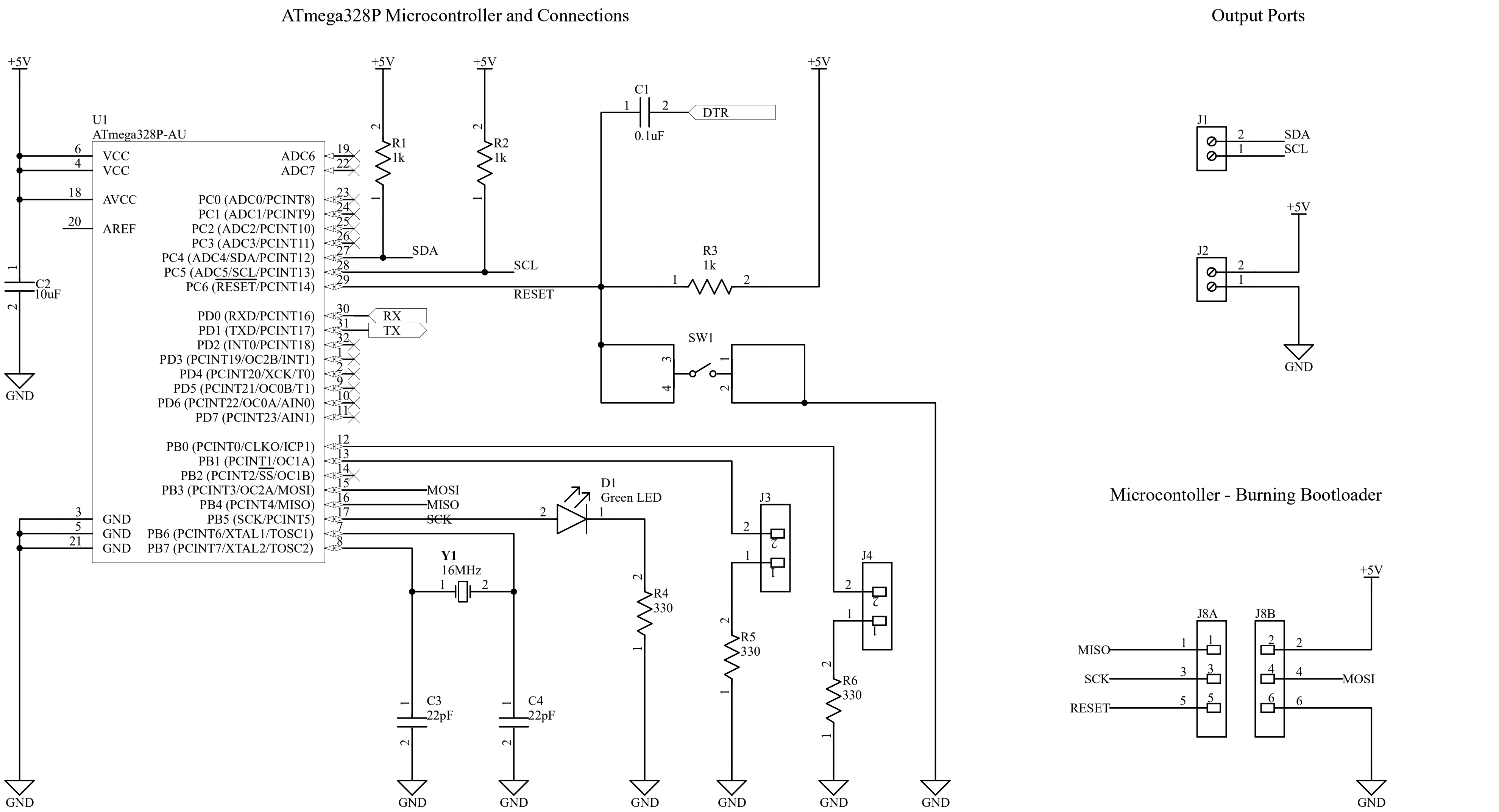
We have designed 2 Schematics for 2 PCBs.

1. Main Controller Schematic
   (a) Top schematic
   (b) MCU ATmega328P-AU schematic
   (c) FTDI schematic
2. IMU (MPU6050 sensor) mount schematic

Schematics are attached in the order shown above



Title	Vibration Analyzer - Main		
Size A4	Number 1		Revision v2.0
Date:	5-19-2024	Sheet of	
File:	D:\GitHub_Projects\..\Main.SchDoc	Drawn By:	Linuka Ratnayake



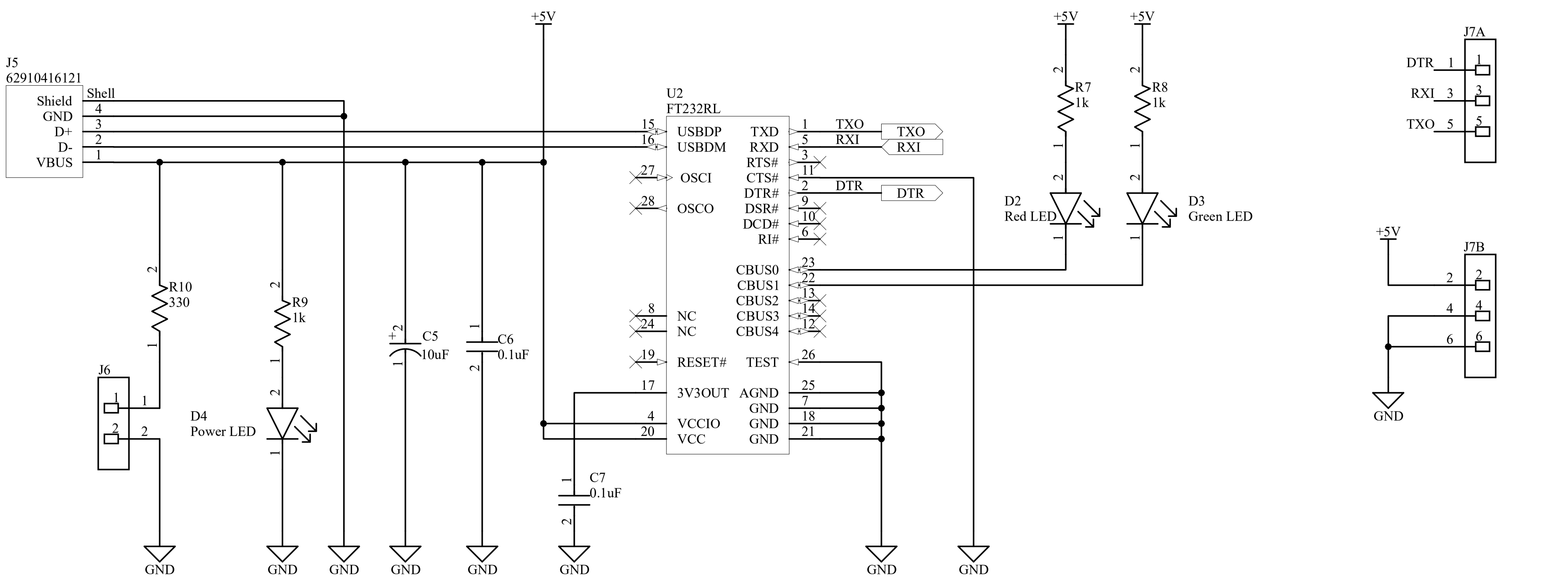
J8A, and J8B extends the SPI pins to faciliatate burning the bootloader to the microcontroller.

J3, and J4 pins can be used to give any kind of indications to the outside.

Title	Vibration Analyzer - MCU Circuit	
Size A4	Number 3	Revision v2.0
Date: 5-19-2024		Sheet of
File: D:\GitHub_Projects\..\ATmega.SchDoc		Drawn By: Linuka Ratnayake

FTDI USB-to-UART Converter

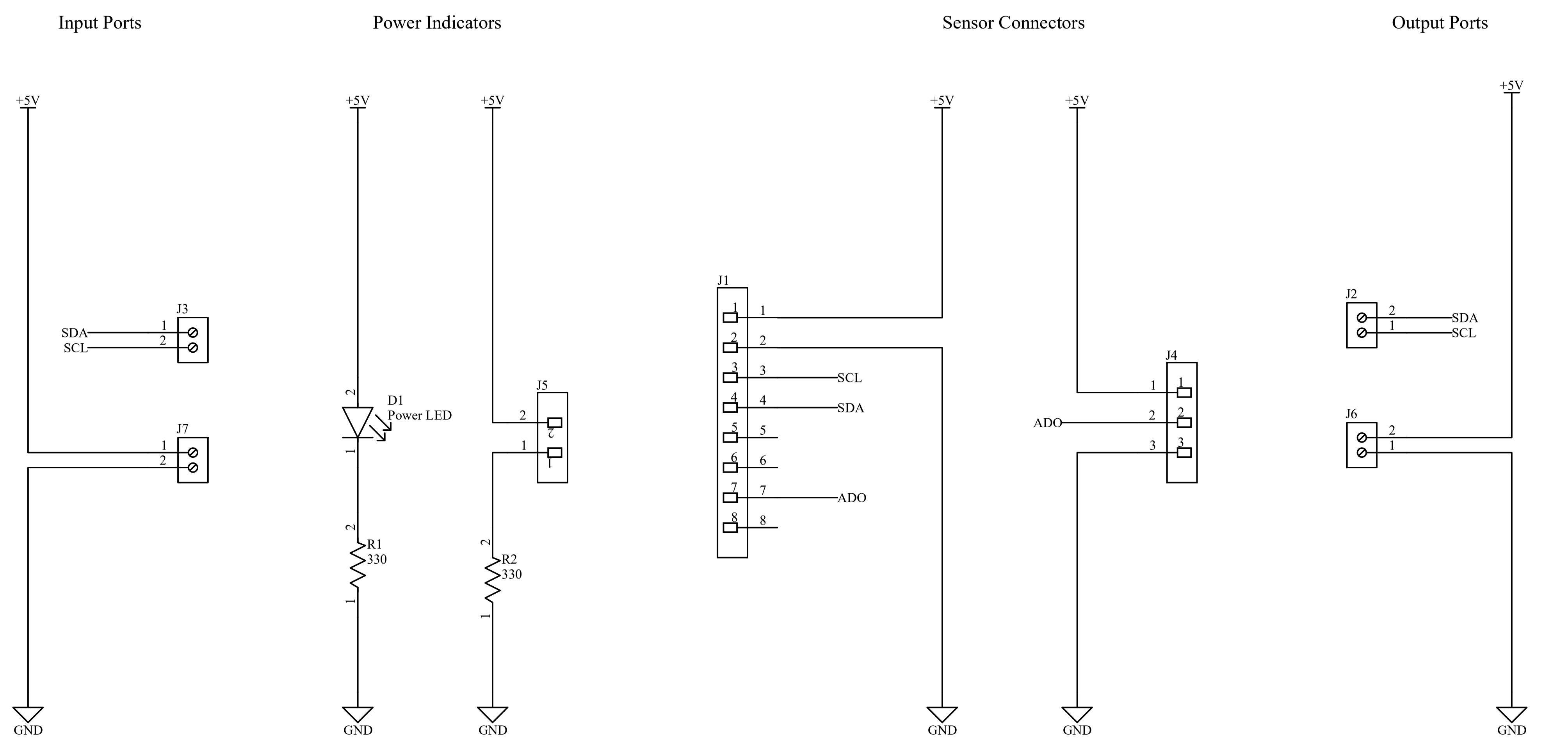
Microcontroller Programming



D4 - Internal, and J6 - External power indicators are used.

J7A, J7B - UART Rx and Tx are connected to external pins, for testing and as a bypass method of programming the microcontroller.

Title: Vibration Analyzer - FTDI Circuit		
Size: A4	Number: 2	Revision: v2.0
Date: 5-19-2024		Sheet of
File: D:\GitHub_Projects\..\FTDI.SchDoc		Drawn By: Sanuja Rupasinghe



One internal and one external power indicators are used.

Input and output ports are placed to facilitate cascading of multiple sensors.

With J1, IMU sensor can be directly soldered or connected using headers.

Title: Vibration Analyzer - Accelerometer Sensor Circuit		
Size: A4	Number: 4	Revision: v2.0
Date: 5-19-2024		Sheet of
File: D:\GitHub_Projects\..\Schematic.SchDoc		Drawn By: Linuka Ratnayake

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