Final Project Report

LE/ENG4000 A - Engineering Project (Capstone)

By:

Project 37: Energy generation using vibration generated at peak hours in crowded places using Piezo sensors.

Table of contents

Executive Summary

In the pursuit of renewable energy solutions, our project focuses on leveraging piezoelectric and force to generate power from vibrations and direct force. Through dedicated research and development efforts, we have engineered a system capable of converting mechanical energy into electrical power and storing it for subsequent use.

Our journey towards the final release has been characterised by iterative refinement and learning. The initial alpha release provided valuable insights, revealing the need for optimization, particularly in enhancing power generation efficiency through a greater number of . This phase served as a foundation for understanding the complexities of piezoelectric energy harvesting and refining our approach accordingly.

Building upon the lessons learned from the alpha release, the development of our final release represents a notable step forward in capability and performance. By increasing the number of , we have improved the pace of power generation, albeit within limitations that surfaced during testing. This enhancement holds promise for applications with moderate power demands.

A notable achievement in our final release is the capability to charge a higher voltage battery, expanding the potential applications of the system. Integration of an active transformer has further elevated the output voltage, albeit within constraints that emerged during testing, reaching levels between 210 to 220 volts. However, despite these advancements, the system still faces challenges in fulfilling higher current requirements, limiting its ability to generate ample power.

The implications of our project extend beyond technological innovation to encompass the exploration of sustainable energy sources. By tapping into mechanical energy from ambient sources, we aim to offer an alternative to traditional power generation methods. However, we acknowledge the current limitations in meeting higher power demands.

Moving forward, our focus remains on enhancing the efficiency, reliability, and scalability of piezoelectric energy harvesting technology. We recognize the need for further optimizations to address current limitations and are committed to exploring new avenues for integration and application.

In conclusion, our project represents progress in the field of energy harvesting, albeit with an awareness of the limitations and challenges encountered. While our final release demonstrates advancements in certain aspects of power generation and storage, it also underscores the need for continued innovation and refinement to realise the full potential of piezoelectric in driving sustainable energy solutions.

Background

Piezoelectric has a fascinating history and significant potential in addressing various challenges, including future energy crises. Here's a background on their development and their potential contributions and a step towards creating clean and sustainable energy for future generations.

Development of Piezoelectric :

Piezoelectricity, the property of certain materials to generate an electric charge in response to mechanical stress, was discovered by the Curie brothers, Pierre and Jacques Curie, in the late 19th century. They observed this phenomenon in crystals such as quartz, topaz, and tourmaline. This discovery laid the foundation for the development of piezoelectricity .

Over the years, advancements in materials science and engineering have led to the creation of synthetic piezoelectric materials with enhanced properties, making them highly sensitive and versatile for various applications. These can now detect subtle mechanical changes, vibrations, and pressures with high accuracy and reliability.

Applications and Contributions in Crisis Management:

Seismic Monitoring: Piezo are extensively used in seismic monitoring systems to detect and analyse ground vibrations, which is crucial for earthquake early warning systems and structural health monitoring of buildings and infrastructure.

Healthcare: In the medical field, piezoelectric cells are used in ultrasound imaging, where they generate and detect ultrasonic waves for diagnostic purposes. They also find applications in wearable health devices for monitoring vital signs and movement patterns.

Industrial Monitoring: Piezo play a vital role in industrial automation and monitoring processes. They can detect machinery vibrations, pressure changes, and material deformations, helping in predictive maintenance and ensuring operational efficiency.

Energy Harvesting: Piezoelectric are utilised for energy harvesting from ambient mechanical vibrations. This technology has the potential to contribute significantly to sustainable energy solutions by converting wasted mechanical energy into usable electrical power.

Smart Cities: In the context of smart cities, piezo can be integrated into infrastructure elements like roads, bridges, and buildings to monitor traffic flow, structural health, and environmental conditions. This data can be used for optimising urban planning and resource management.

In conclusion, piezoelectricity has evolved from a scientific curiosity to indispensable components in various industries and applications.

Sustainability Impact

Piezo offers a promising solution to the energy problem by tapping into the untapped potential of mechanical vibrations. These possess the unique ability to convert mechanical energy, in the form of vibrations or movements, into electrical energy. This conversion process is achieved through the piezoelectric effect, where certain materials generate an electric charge in response to applied mechanical stress.

By harnessing this inherent property, piezo can capture ambient vibrations from various sources, such as footsteps, vehicle movements, or machinery operations, and convert them into usable electrical power.

Additionally, piezo offer a sustainable energy solution. Unlike fossil fuel-based power generation, which contributes to environmental pollution and resource depletion, piezo-based energy harvesting is clean and renewable. It reduces reliance on non-renewable resources and minimises environmental impact, aligning with global sustainability goals.

Here's how the project aligns with some of the United Nations Sustainable Development Goals (SDGs):

Goal 7: Affordable and Clean Energy
The project promotes clean energy by harnessing mechanical vibrations to generate electricity, contributing to sustainable energy practices.

Goal 11: Sustainable Cities and Communities
The project's energy harvesting system can be integrated into urban environments, providing sustainable power solutions for communities and contributing to resilient infrastructure.

Goal 12: Responsible Consumption and Production
The system promotes responsible consumption by efficiently converting mechanical energy into electrical energy, optimising resource use and reducing waste.

Goal 13: Climate Action
By utilising renewable energy sources and reducing reliance on fossil fuels, the project supports efforts to mitigate climate change and reduce greenhouse gas emissions.

Goal 17: Partnerships for the Goals
Collaboration with stakeholders, including technology providers, researchers, and communities, is essential for the success and scalability of the project, aligning with the goal of fostering global partnerships for sustainable development.

These alignments showcase the project's contribution to broader sustainability objectives and its potential impact on addressing key global challenges.

Design Problem

Design Problem Statement

In light of the rapid growth of IoT and MEMS devices, there is a rising demand for autonomous power solutions. Wired systems are often impractical due to their limitations and costs, especially for low-power applications. To address this, we propose harnessing ambient mechanical vibrations as a renewable energy source to supplement existing power methods for these devices.

Objective

Our objective is to design a scalable module system that can operate in diverse environments and applications, providing a universal energy harvesting solution. The proposed system will utilise passive elements and be easily deployable, requiring minimal setup and maintenance. The output interface will be adaptable to various devices.

Key Design Challenges

Modularity: Ensuring that the system components are modular and easily integrable into different environments and applications.
Scaling: Designing the system to scale effectively, accommodating varying power requirements and environmental conditions.
Power Generation: Generating sufficient power from mechanical vibrations to meet the energy demands of power devices consistently.

Performance Metrics

The success of the system will be evaluated based on the following key performance metrics:

Reliability: Measured by mean uptime, indicating the system's ability to consistently operate without downtime.
Robustness: Evaluated by the time between instances of system breakage or malfunction, showcasing the system's durability.
Power Generation: Assessed by the average power output, ensuring that the system can meet the energy needs of connected devices effectively.

User Requirements

After the first Alpha release of the design, we conducted a small survey set to figure out what were the users expecting from the design and from the system itself. Based on the user input we had some requirements to fulfil in our final design.

User Requirements	Main aspects	Percentage fulfilled
Efficient Power Generation	- Efficiently harness mechanical energy from surroundings - Generate sufficient electrical power to meet the intended application's requirements.	75%
Real-time Monitoring and Feedback	- Provide a clear representation of the energy harvesting process. - Ensure intuitive way to monitor the system	60%
Battery Storage Capacity	- Provide a high-capacity battery for efficient storage of harvested electrical energy. - Ensure batteries can power intended applications for extended periods, offering reliable energy storage solutions.	90%
Output Voltage Regulation	- Include circuitry to convert stored electrical energy into higher output voltage (210 to 220 volts). - Ensure that the power is regulated within specified range consistently for compatibility with devices requiring elevated voltage levels.	80%
Reliability and Durability	-Ensure system exhibits robustness and durability, capable of withstanding various environmental conditions and operational stresses. - Select and integrate components for long-term	30%*****

	reliability and minimal maintenance requirements.	
Scalability and Adaptability	-Design system to be scalable to accommodate varying power generation requirements and environmental conditions. - Allow flexibility to adapt systems to different applications and scenarios with modular and customizable features.	30%*****
Safety and Compliance	- Adhere to relevant safety standards and regulations to ensure user and environmental safety.	20%*****
Ease of Installation and Integration	- Provide a system that is easy to install and integrate into existing infrastructure or applications. - Minimise downtime for maintenance	30%*****
Cost-effectiveness	- Offer cost-effective solutions for energy harvesting, balancing initial investment with long-term benefits and return on investment. - Consider maintenance, operation, and lifecycle costs over the system's expected lifespan.	70%

*Note * :- The lower percentages are due to the current open circuit representation of the final design, these numbers will change after being able to enclose the design in an enclosure like a final product and extend the harvesters in modular tiles as anticipated.*

System Requirements

The system requirements for the design has changed after the alpha release for the project due to addition of some newer components. The system now has active feedback representation in order to show how much force is being applied and showing the number of applied steps on the harvesters.

The design also is able to produce high voltage levels in the system which adds up to the requirements for the system to sustain such a device to control it as well.

System Requirements	Explanation
Increased number of Piezoelectric	Efficiently convert mechanical energy from ambient vibrations and direct force into electrical power, as more are required in order to generate a sufficient amount of energy.
Visual representation and controller	Provide real-time monitoring and feedback on the energy harvesting process, including the number of steps taken (if applicable) and the force applied to the .
Battery Charging Circuit	Include boost converter to elevate voltage output from piezoelectric for efficient charging of high-capacity battery.
High-Capacity Battery	Store harvested electrical energy efficiently for later use, providing reliable energy storage solutions for extended periods.
Output Voltage Regulation Circuit	Convert stored electrical energy into higher output voltage (210 to 220 volts) and regulate output voltage within specified range consistently.
Low Power Consumption:	Ensure the system itself consumes minimal power to maximise energy efficiency and optimise power generation capabilities. (using low power dissipating components)

These requirements are in compliance with the final design for the circuit in order to make sure that the designer is able to achieve the basic requirements to re-create the circuit as explained ahead and achieve similar results.

Product Vision Board

VISION

We are inspired by the potential of piezoelectric technology to harness ambient energy and contribute to a greener future. By developing this product, we aim to address the challenges of energy sustainability and offer a viable solution that aligns with our commitment to environmental stewardship.
By tapping into ambient vibrations and direct force, it offers a sustainable alternative to traditional energy sources, reducing reliance on fossil fuels and mitigating carbon emissions.

TARGET GROUP	NEEDS	PRODUCT	BUSINESS GOALS
The product targets the renewable energy market segment, specifically focusing on energy harvesting solutions. It caters to industries and applications where the integration of sustainable energy sources is paramount, such as renewable energy infrastructure.	**Problem it Solves:** Reduces reliance on traditional energy sources and mitigates carbon emissions by harnessing ambient vibrations and force for power generation. **Benefits it Brings:** Offers a sustainable and efficient energy harvesting solution, enabling increased autonomy and reducing environmental impact.	Piezoelectric energy harvesting system. 1. Harnesses ambient vibrations for power generation. 2. Real-time monitoring and feedback capabilities. 3. High-capacity battery for energy storage. 4. Output voltage regulation for compatibility with various devices.	Enhances reputation as an innovative and sustainable energy solutions provider, potentially leading to increased market share and profitability. Increase revenue through product sales, penetrate new markets in renewable energy and IoT sectors.

Our product envisions a greener future by harnessing the potential of piezoelectric technology to generate energy from ambient vibrations and force. It addresses the pressing challenges of energy sustainability by offering a sustainable alternative to traditional energy sources, thereby reducing reliance on fossil fuels and mitigating carbon emissions.

Our product is aimed at the renewable energy market segment, which includes end users, engineers, environmentalists, manufacturers of IoT devices, smart city initiatives, and industries. Its goal is to empower sustainability and innovation. Through real-time monitoring and feedback capabilities, it offers observable advantages like enhanced autonomy, decreased environmental impact, and operational efficiency. Our piezoelectric energy harvesting system is poised to transform the renewable energy landscape and make a significant contribution to a more sustainable and environmentally friendly world thanks to its scalable and adaptable design.

TECHNICAL VOLUME

System Overview and Functionality

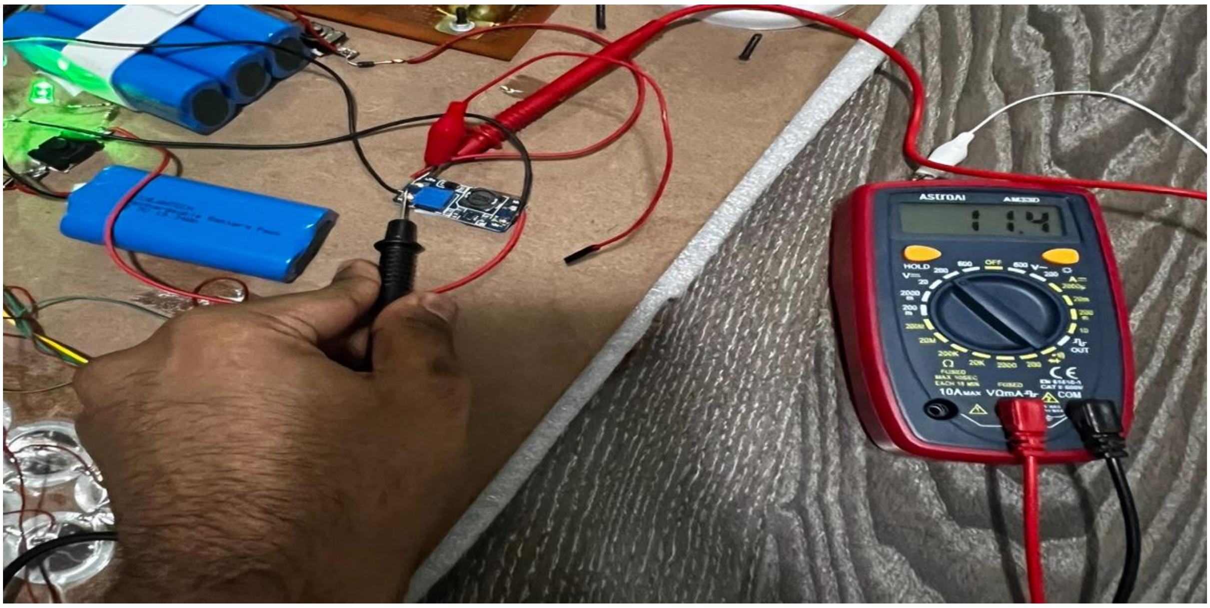
The Main Functionality of the system is as follows :-

1. Piezo generate energy when force is applied to them.
2. The generated energy is stored in a 3.7V lithium-ion rechargeable battery charged by the Piezo-.
3. A voltage booster is used to increase the voltage from 3.7V to 11V.
4. The 11V is used to charge 11.1V rechargeable batteries.
5. The 11.1V DC output is then converted into 220V AC using an inverter transformer circuit.
6. The Voltage and Count of Footsteps are shown on the LCD screen with Arduino UNO and Multimeter.
7. The 220V output can be utilised to power various devices and sources.

This integrated system efficiently converts mechanical energy into usable electrical power, providing a versatile and sustainable energy solution for diverse applications.

System Architecture

The system operates by harnessing energy through piezo , which generate electrical energy when subjected to mechanical force. This energy is then stored in a 3.7V lithium-ion rechargeable battery for efficient utilisation. To optimise power output, a voltage booster 4V DC- 12V DC is employed to increase the stored voltage from 3.7V to 11.4V which is charged with Piezo providing steady DC voltage of around 2.68 V- 3.02V.



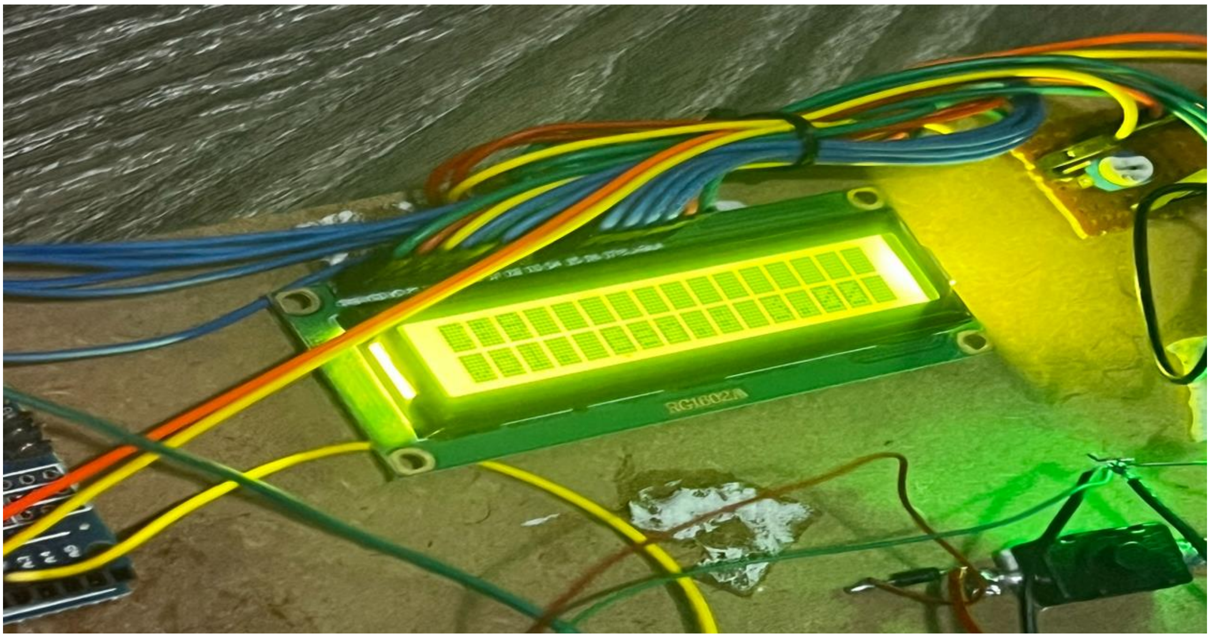
(Figure 1 - Voltage Booster Showing 11.4V DC Steady Voltage from 3.7 V battery)

The steady 11.4V output is utilised to charge 11.1V rechargeable batteries, maintaining a continuous and sustainable power flow. Subsequently, the 11.1V DC output undergoes a crucial transformation through an inverter transformer circuit which is configured in such a way with the help of variable resistors R1 and C1. The IC CD4047 CMOS multivibrator acts as a switching pulse oscillating device while the MOSFET IRFZ44n in the DC inverter circuit acts as a switch. The 12-0-12V transformer inversely used as a step up transformer, converting it into a potent 220-250V AC output. This conversion enables the system to power a diverse array of devices and applications that require higher voltage levels, adding versatility to its functionality.

(Figure 2 - Multimeter showing Voltage Output of 232V AC voltage)

To monitor and control the system's performance effectively, an Arduino UNO with LCD screen at positive and negative end of piezo- while Multimeter at the output ports are integrated, providing real-time feedback on voltage levels and step counts. This monitoring capability ensures efficient management and utilisation of the generated energy.
In summary, this high-level architecture encompasses energy generation, storage, voltage optimization, conversion, monitoring, and control, making it a comprehensive and robust system for powering various applications with ease and efficiency.

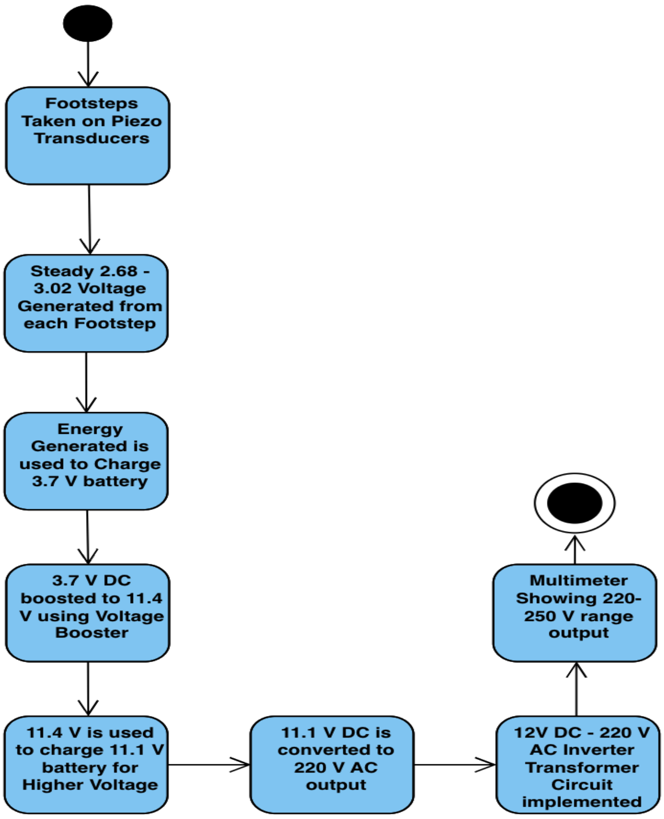
The Arduino Uno's affordability and accessibility make it a practical option for integrating into our project. Its compatibility with a wide range of programming languages and libraries simplifies the development process and allows for rapid prototyping and iteration, including our energy harvesting system as well. Its open source nature , Compatibility with different types of IOT devices , Circuits and makes it a more user friendly platform to use.



(Figure 3 - Arduino LCD showing Steady Voltage of 3V and 9 Footsteps by)

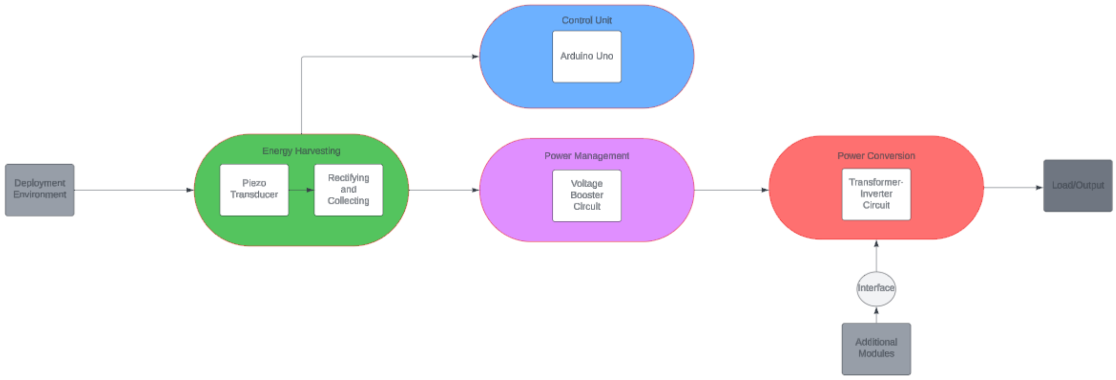
The UML activity diagram was used to visually represent the sequence of steps and activities involved in the energy harvesting system

UML Diagram



(Figure 4 - UML Activity Diagram)

System Interface Protocol



(Figure 5 -Sytems Interaction)

The system interface depicted in the above diagram can be categorised into several key components: Energy Harvesting, Power Management, Control Unit, and Power Conversion.

Energy Harvesting: This segment of the architecture utilises an array of piezo , which are designed to convert mechanical stress into electrical energy. The are connected in a configuration that maximises the harvested energy from environmental vibrations.

Power Management: The harvested energy, which is initially at a variable low voltage, is then directed to a voltage booster circuit. This circuit elevates the low voltage from the piezo to a stable level suitable for charging the batteries. Two battery systems are depicted: a 3.7V battery and a 11.1V battery, both of which are managed to ensure they are properly charged without overcharging, as indicated by the presence of diodes and capacitors for regulation.

Control Unit: At the heart of the control unit is an Arduino Uno, which is interfaced with a 16X2 LCD display. This subsystem is responsible for monitoring and displaying the voltage levels, as well as potentially managing the distribution of power to the different components within the system.

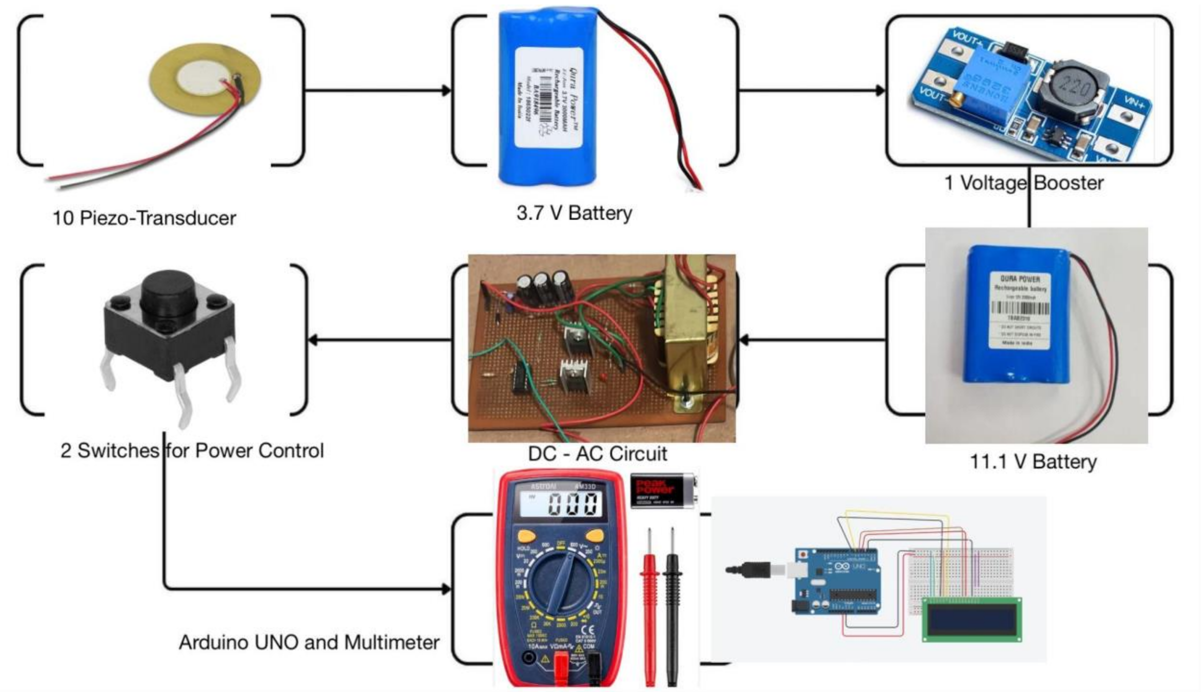
Power Conversion: The final category is the power conversion section, which converts the 11.1 V DC from the batteries to 220V AC through an inverter circuit. This part of the system includes a transformer, switching transistors, and other components such as resistors and capacitors to facilitate the conversion process. The converted power is then suitable for running AC devices, which could include cameras and other monitoring equipment.

Overall, the system's architecture is strategically designed to harness, manage, and convert energy in a manner that makes it suitable for powering electronic devices, emphasising efficiency and sustainable energy use and making it easy for the user to understand how each individual component of the system interacts with each other. More diagrams including wire schematics, flowcharts are shown below to understand the system in more detail

The flowchart visually represents the sequential steps and components involved in the energy harvesting system. Each component image in the flowchart corresponds to a specific function or task within the system, such as the piezo for energy generation, the lithium-ion rechargeable battery for energy storage, and the voltage booster for increasing voltage levels, DC-AC circuit for 12V DC to 220 V AC output and Arduino UNO and multimeter showing the output Voltage and Footsteps taken.

The flowchart demonstrates how these components are interconnected and the flow of energy from generation to utilisation. It serves as an intuitive guide to understand the system's workflow and the role of each component in the overall operation of the energy harvesting process.

CodeBlock Design - (Component Flowchart)

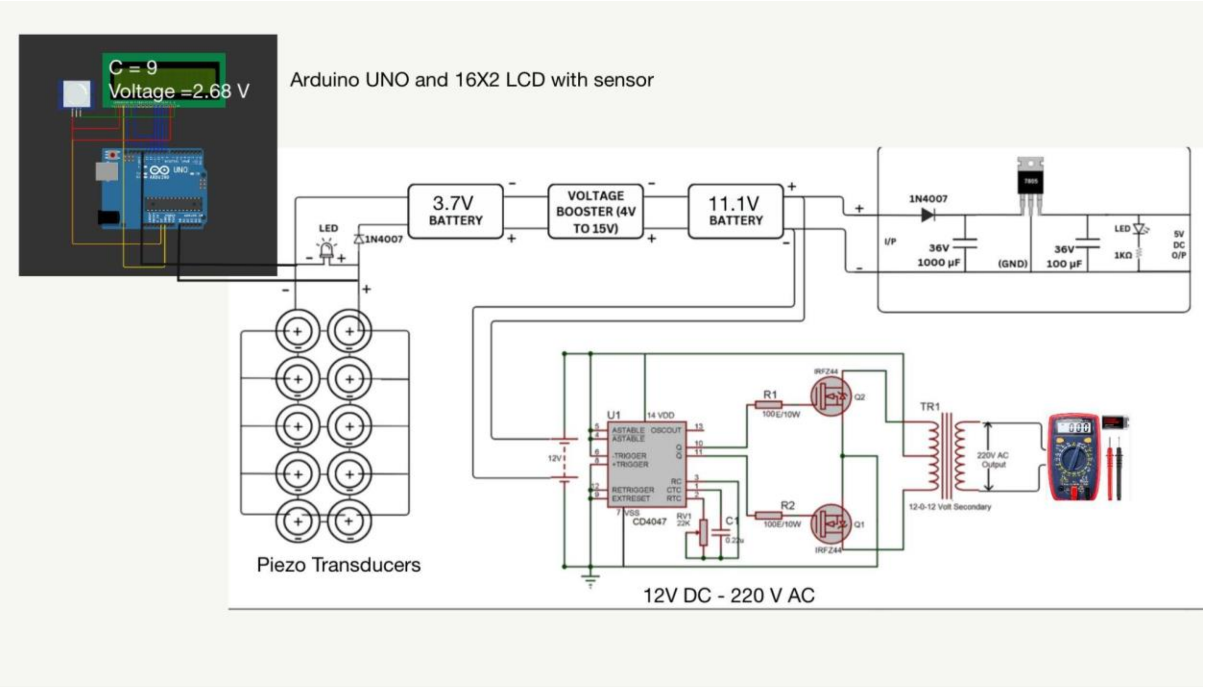


(Figure 6 - Component Workflow Diagram)

The wiring schematic for our energy harvesting system is meticulously designed to ensure efficient and reliable operation. It reflects our commitment to applying engineering principles and best practices to solve complex energy conversion challenges. The schematic illustrates the interconnection of key components such as piezo , voltage boosters, rechargeable batteries, inverter circuits, and monitoring systems using Arduino UNO microcontrollers. Each component's role and connectivity are clearly defined, ensuring a coherent and optimised system configuration.

By documenting the wiring schematic in detail, we facilitate easy replication and understanding for future development and troubleshooting. Additionally, the schematic aligns with sustainability goals by promoting energy efficiency and resource optimization. It serves as a visual representation of our innovative solution, showcasing creativity and effective communication in our design approach.

Wiring Schematic - (Final Release)



(Figure 7 - Wiring Schematic for the final release with all components)

Pin LCD Descriptions: for Arduino LCD screen and how they are connected which is shown in the above wiring schematic and below is the code with Arduino UNO

```
* Pin 1 --- Ground - transducers -ve PIN + Ground Arduino
* Pin 2 --- VDD Power for the LCD - transducers +ve PIN + Arduino +5V PIn
* Pin 3 --- Contrast Adjust - GND Arduino PIN
* Pin 4 --- Register Select (RS) - 13 on Arduino UNO
* Pin 5 --- Read / Write select (R/W) - transducers -ve pin
* Pin 6 --- Enable (E) - 12 on Arduino UNO
* Pin 7 --- not used
* Pin 8 --- not used
* Pin 9 --- not used
* Pin 10 -- not used
* Pin 11 -- Data line (D4) 4-bits at a time - ~11 on Arduino UNO
* Pin 12 -- Data line (D5) 4-bits at a time - ~10 on Arduino UNO
* Pin 13 -- Data line (D6) 4-bits at a time - ~9 on Arduino UNO
* Pin 14 -- Data line (D7) 4-bits at a time - ~8 on Arduino UNO
* Pin 15 -- Backlight Power - transducers +ve PIN + Arduino UNO 5V PIN
* Pin 16 -- Backlight Ground (GND) remember 220 ohms resistor - transducers -ve PIN
*
*/
```

Code for Arduino UNO with 16X2 LCD screen

```
// library for liquid crystal display 16 X 2 LCD

#include <LiquidCrystal.h>

// Initialize the LCD screen with the pin

LiquidCrystal lcd(12, 11, 5, 4, 3, 2);

// Variables to store footsteps and voltage

int footsteps = 0;
float totalVoltage = 0.0;
const int transducersPin = A0; //  the tap transducers is connected to analog pin A0

void setup() {

 // Setting up the LCD screen columns and rows for displaying the results taking the input
from transducers
  lcd.begin(16, 2);
  pinMode(transducersPin, INPUT);
}

void loop() {
  // Read the analog value from the pressure transducers which detects the thrust from
footsteps

 int transducersValue = analogRead(transducersPin);

 // Map the analog value to voltage based on thrust range

  float voltage = map(transducersValue, 0, 1023, 0, 4); // 0-4V range

// Update total voltage and footsteps as the footsteps increases and voltage changes
according to transducers value

  totalVoltage += voltage;

 footsteps++;
    voltage += voltagePerStep;

 // Display footsteps and voltage on the LCD screen on first and second rows

  lcd.clear();
    lcd.setCursor(0, 0);
    lcd.print("C = ");
    lcd.print(footsteps);
```

```
    lcd.setCursor(0, 1);
    lcd.print("V = ");
    lcd.print(voltage);
    delay(1000); // Delay for the results to display on screen
  }
}
```

Previous Iterations and System Evolution

Our project traces the evolution of an energy harvesting system, from initial concepts to refined implementations, aimed at converting mechanical vibrations into electrical energy for practical use. Initially conceptualised to harness everyday kinetic activities in crowded spaces, the project faced numerous challenges that shaped its development through successive iterations.

Starting with theoretical simulations, the project moved through various phases, adapting to the realities of piezoelectric materials and their potential for energy conversion. Each phase brought valuable insights, leading to significant design adjustments aimed at improving system efficiency and sustainability.

This section outlines our project's journey, highlighting the iterative design process and the adaptations made to overcome technical challenges and optimise performance. This narrative underscores our dedication to the engineering process and trial and error as we strive for continual improvement in sustainable energy solutions.

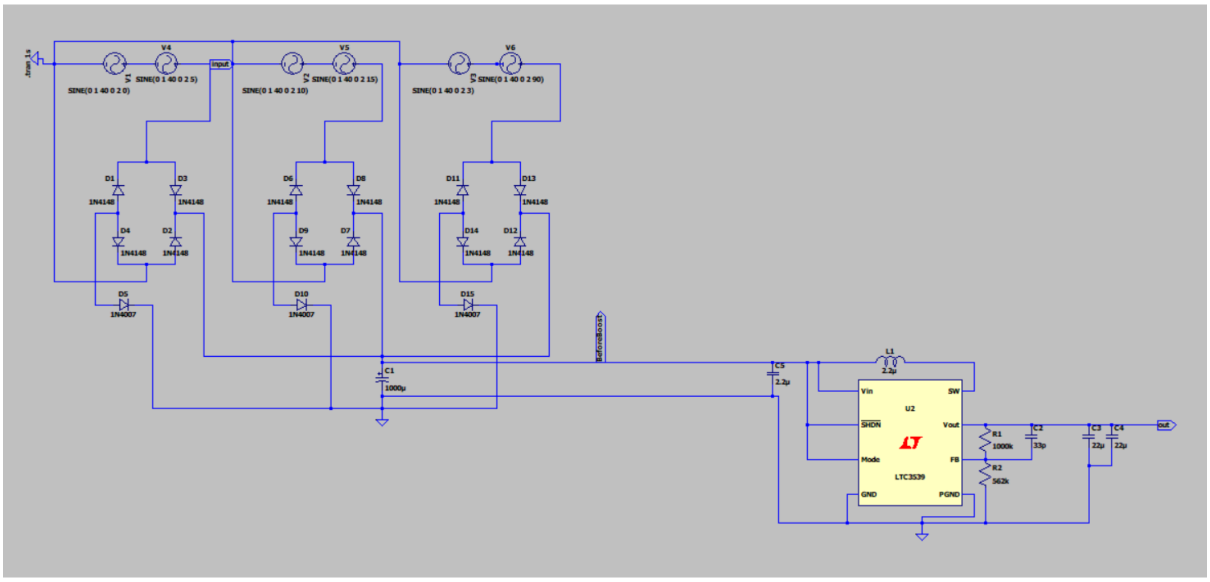
Initial Simulation Phase

The project embarked on its journey with a simulation phase designed to establish a theoretical groundwork for piezoelectric energy harvesting. Utilizing PSpice, the team aimed to model the behavior of piezoelectric transducers under varied real-world conditions.

Simulation Objectives and Setup:

Goal: To predict the output capabilities of piezoelectric transducers when subjected to the typical vibrations found in crowded urban settings.

Methodology: The simulation employed a virtual PSpice model of piezoelectric transducers arranged in a combination of series and parallel configurations to evaluate the effectiveness of energy capture from ambient vibrations.



(Figure 8 - LTSpice Simulation Alpha Release)

Circuit Summary:
We've configured six voltage sources with two in series and three sets in parallel to optimise cost-efficiency per harvester. These sources generate AC voltage, so we've incorporated a low-power rectification circuit using Schottky diodes, which minimises power loss. Each pair of series-connected actuators is equipped with its own rectifier to prevent interference.

The output from these rectifiers is smoothed by a large electrolytic capacitor, eliminating any voltage spikes or fluctuations and ensuring a stable DC output. The system employs a boost converter, specifically the LTC3539 switching boost converter, which efficiently elevates the voltage from a low input range of 0.9 to 3 V up to a consistent 3 - 5 V DC, suitable for our application requirements.

Simulation Results:

- The peak to peak voltages of all the 6 actuators peaked around 1- 2 V (randomly selected) , to get as much entropy in the system as possible.
- The stable DC voltage at the capacitor was expected to be between 0.978 - 1.12 V which was significant enough to be boosted using a boost converter without any independent power sources.
- After the Boost conversion we expect a voltage between ~ 3.3V - 3.6 V which can be utilised as a high voltage , low current power source to slow charge a battery or so.

First Practical Implementation: Vibration transducers Circuit

Following the initial simulation phase, the project transitioned to the practical implementation of a vibration transducers circuit. This phase involved constructing and testing a circuit designed to harness mechanical vibrations using piezoelectric transducers in an urban setting.

Circuit Design and Configuration:

- transducers Arrangement: The circuit incorporated six piezoelectric transducers configured in two series, each with three transducers in parallel. This layout was chosen to optimise the capture of ambient vibrations while keeping the costs low.
- Energy Conversion Components: The circuit used Schottky diodes for rectification because of their low power consumption and high efficiency, essential for minimising energy loss in low-output systems. Each series of transducers was equipped with its own rectifier to prevent interference and ensure a more stable output.

Challenges with Vibration transducers Output

The initial implementation of the vibration transducers circuit using film vibration-based MEMS transducers revealed significant challenges that necessitated a reevaluation of the system's design. Despite the theoretical potential of these transducers, practical application exposed critical limitations in their performance.

transducers Limitations:

The MEMS transducers utilized in our system were too small to effectively detect and respond to changes in voltage levels at their resonance frequency. This limitation in transducers choice led to insufficient energy capture, undermining the effectiveness of the energy harvesting system. Additionally, even when these transducers were deployed in large arrays, the overall energy output remained disappointingly low. This outcome underscores a critical flaw in the selection process and questions the suitability of these transducers for the intended application.

Circuit Design Issues:

One significant contributor to power loss in our system was the full bridge rectifier used in the circuit. Although designed to convert AC to DC efficiently, the rectifier exhibited notable efficiency losses according to its datasheet specifications, significantly impacting the net power available for charging and other applications. Additionally, the smoothing capacitors associated with the rectifier, intended to stabilize the output, further contributed to energy loss. These components were not optimally suited to the low-power output from the transducers, leading to additional inefficiencies.

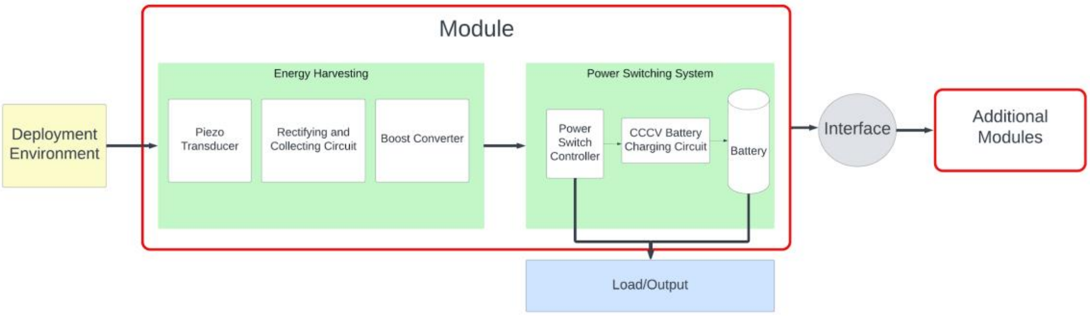
Impact on Project Goals:

The challenges encountered with the vibration transducers and energy conversion components significantly hindered the project's capacity to achieve efficient energy harvesting. The inadequate power generation capability highlighted the need for a thorough redesign of the system, focusing on selecting more effective technologies and components to fulfill the project's energy requirements. This phase of the project was instrumental in recognizing the practical limitations of the chosen technologies, emphasizing the necessity for a strategic shift in design philosophy to investigate alternative solutions that could improve the system’s performance.

Transition to Force transducers: Alpha Release Implementation

The Alpha Release of the project marked a significant shift in focus, implementing a single force transducers to establish a baseline for energy harvesting capabilities. This phase aimed to test the viability of force transducers for energy generation before expanding to a larger array.

Alpha Release System Architecture Overview:



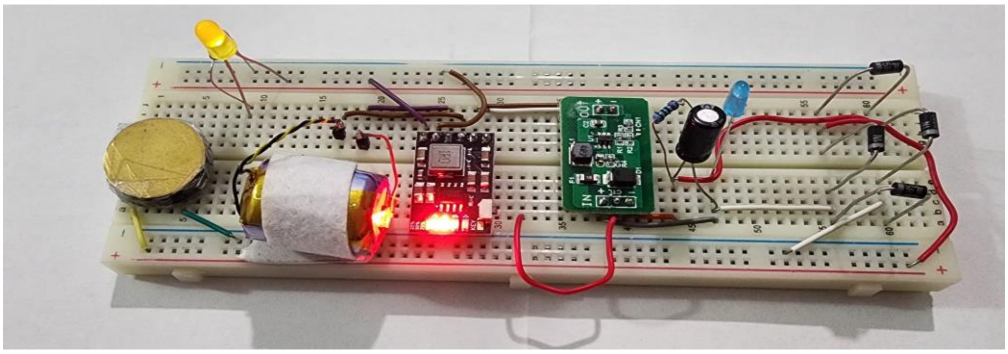
(Figure 9 - System Interface Alpha Release)

Modular Design: The system architecture was modular, with each unit comprising an energy harvesting circuit. These modules can then be connected to a power switching system to store and use the harvested energy. This design allowed for scalability through parallel attachment of additional modules.

System Implementation:

In the initial implementation during the Alpha Release, the project utilized a single force transducer to validate the concept. This transducers was integrated onto a breadboard to assess its functionality and effectiveness in harnessing mechanical force. The output from the transducers underwent rectification to convert it into usable electrical energy. Subsequently, the rectified output was directed into a boost converter to elevate the voltage level for efficient energy utilization. We incorporated a rudimentary visual feedback element to provide immediate indication of the system's operation. An LED indicator was included to visually signal the conversion of mechanical force into electrical energy.

For energy storage, the charging mechanism was designed to accommodate a single lithium-ion battery. This simplified setup allowed for a focused evaluation of charge storage efficiency under the influence of the force transducers. By using a single battery, the project aimed to gauge the system's ability to store harvested energy effectively and reliably.



(Figure 10 -Alpha Release Circuit)

Challenges Faced by the Alpha Release

Limited transducers Configuration:
The Alpha Release's reliance on a single transducers restricted the system's ability to capture energy efficiently from mechanical vibrations. This limitation resulted in suboptimal energy generation capacity.

Suboptimal Rectification Stage:
The use of prebuilt bridge rectifiers in the Alpha Release led to significant power loss due to heat dissipation. This inefficiency in the rectification stage reduced the overall energy conversion efficiency of the system, impacting its performance and reliability.

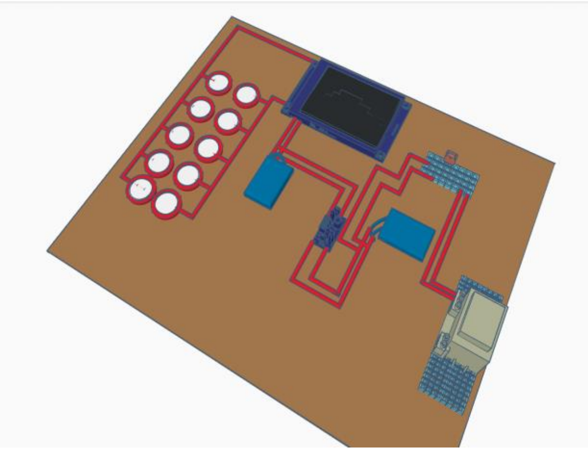
Insufficient Monitoring and Control:
The rudimentary monitoring and control mechanisms in the Alpha Release lacked real-time feedback and comprehensive data logging capabilities. This limitation restricted the system's ability to track performance metrics and diagnose operational issues, hindering overall efficiency and management.

Limited Computational Resources:
Without computational resources such as microcontrollers or data processing units, the Alpha Release lacked the ability to implement advanced control algorithms or

interface with external devices. This constraint limited the system's adaptability and responsiveness to changing operating conditions, impacting its overall functionality and versatility.

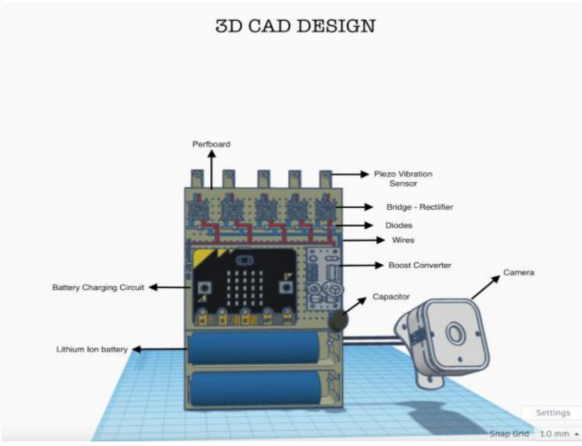
CAD Models

CAD Model - Final Release



(Figure 11 - CAD Model Final Relase)

CAD Model - Alpha Release Prototype

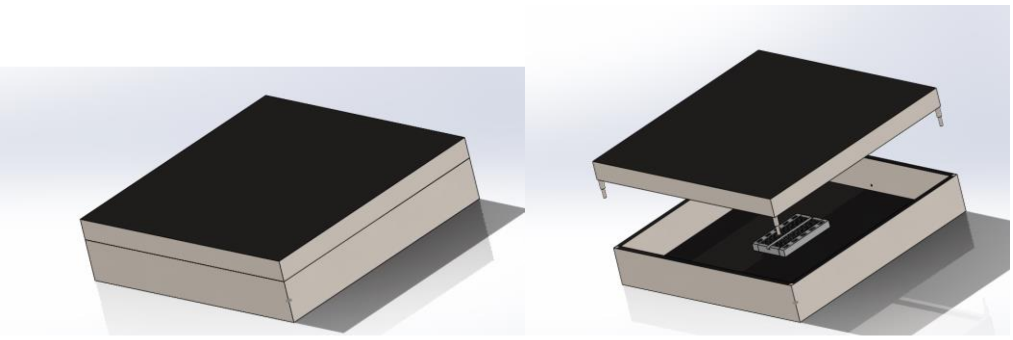


(Figure 12 - CAD Model Alpha Prototype)

Final Release CAD Model: Our latest Tinkercad CAD model is the result of extensive design improvements, featuring advanced functionality and user-friendly design.
Alpha Release Prototype CAD Model: The Tinkercad prototype helped us test basic ideas and lay the groundwork for our final product's development showing below with casic designs that we planned to release in our alpha prototype but deviated from that idea due to unintended consequences.

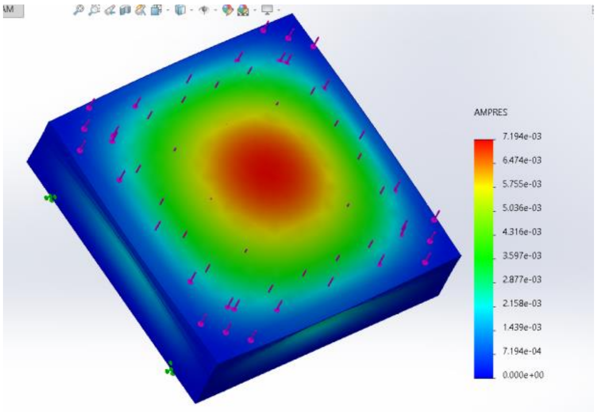
Casing: (Alpha Release)

Entire Assembly



(Figure 13 -Casing 3D Prototype)

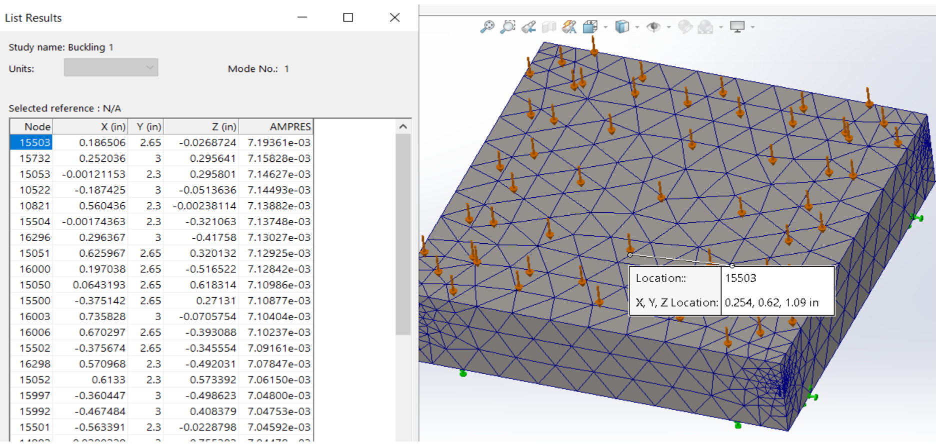
Exploded view



(Figure 14 - Exploded View of Casing)

Resulted deformation of the casing unit (in) uniform force considered

Deformation on the Casing



Node	X (in)	Y (in)	Z (in)	AMPRES
15503	0.186506	2.65	-0.0268724	7.19361e-03
15732	0.252036	3	0.295641	7.15828e-03
15053	-0.00121153	2.3	0.295801	7.14627e-03
10522	-0.187425	3	-0.0513636	7.14493e-03
10821	0.560436	2.3	-0.00238114	7.13882e-03
15504	-0.00174363	2.3	-0.321063	7.13748e-03
16296	0.296367	3	-0.41758	7.13027e-03
15051	0.625967	2.65	0.320132	7.12925e-03
16000	0.197038	2.65	-0.516522	7.12842e-03
15050	0.0643193	2.65	0.618314	7.10986e-03
15500	-0.375142	2.65	0.27131	7.10877e-03
16003	0.735828	3	-0.0705754	7.10404e-03
16006	0.670297	2.65	-0.393088	7.10237e-03
15502	-0.375674	2.65	-0.345554	7.09161e-03
16298	0.570968	2.3	-0.492031	7.07847e-03
15052	0.6133	2.3	0.573392	7.06150e-03
15997	-0.360447	3	-0.498623	7.04800e-03
15992	-0.467484	3	0.408379	7.04753e-03
15501	-0.563391	2.3	-0.0228798	7.04592e-03

(Figure 15 - Deformation 3D Diagram)

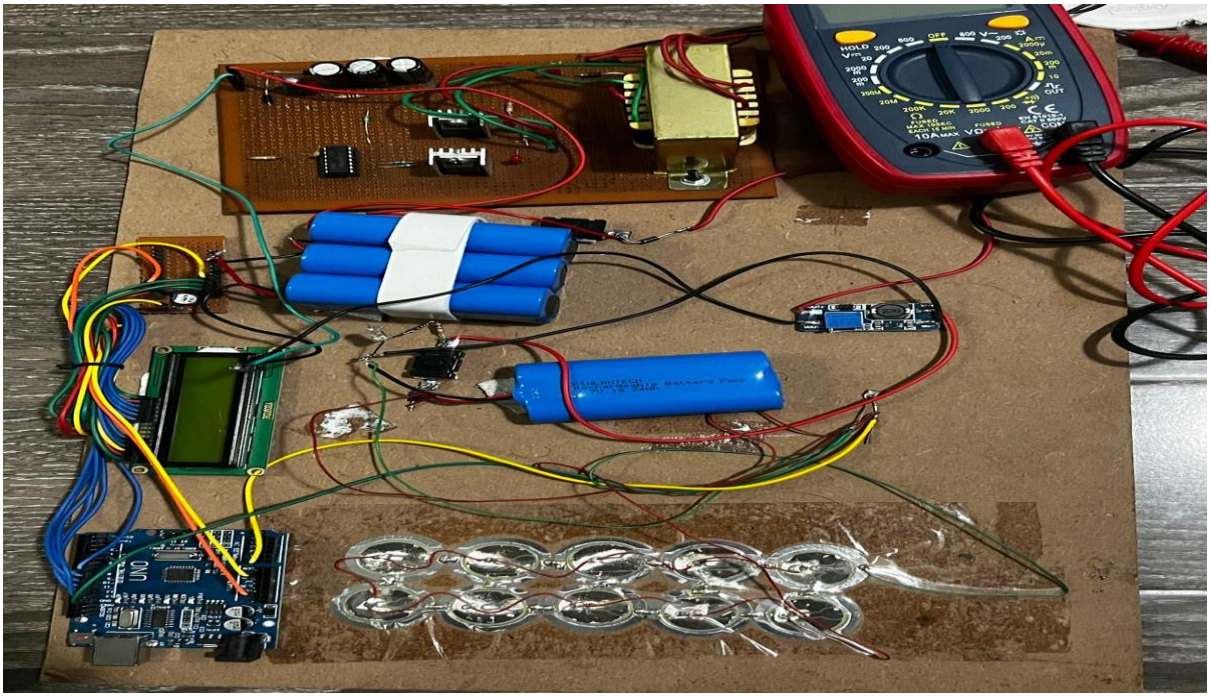
In the development of the piezoelectric energy harvesting device, a thorough investigation was conducted to evaluate the impact of vibrations on the device's casing. The study aimed to ensure that the mechanical stress transmitted to the piezoelectric would be sufficient to generate the required electrical energy. However, the findings revealed that the casing is over engineered, presenting an unexpected challenge: the strength and rigidity of the casing material are such that it does not undergo enough deformation to create adequate vibrations for energy generation which led us to deviate from the casing plan for our final rel

The lack of deformation implies that the are unable to accumulate and convert mechanical energy from natural vibrations into electrical power effectively. In energy harvesting, it is crucial for the casing to have a certain level of flexibility or susceptibility to vibrational forces to capitalise on the piezoelectric effect. The stiffness, while beneficial for protecting internal components from physical damage, inadvertently hinders the device's core function of energy conversion.

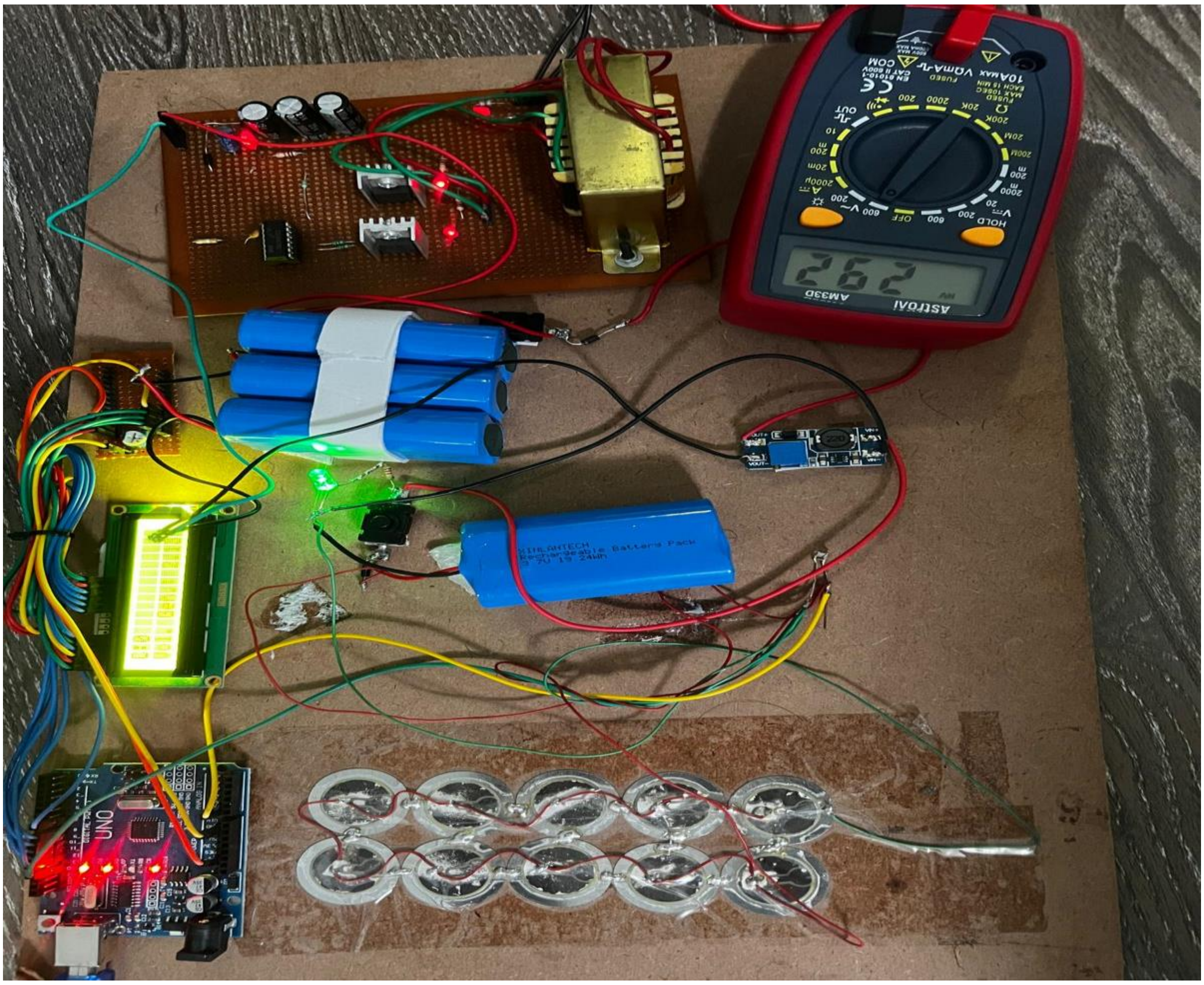
To address this issue, a redesign of the casing may be necessary. Options could include the use of a material with a lower Young's modulus to allow more flex, incorporation of design elements that facilitate better transmission of vibration, or even structurally engineered weak points where vibrations could be maximised without compromising the overall integrity of the device.

In conclusion, while the current casing ensures durability, its excessive strength is a detriment to the functionality of the piezoelectric energy harvesting system. A careful balance must be struck between protection and performance, necessitating further design revisions to optimise the energy generation capability of the device.

(Final Release)



(Figure 16 - Final Release Energy Harvesting Circuit)

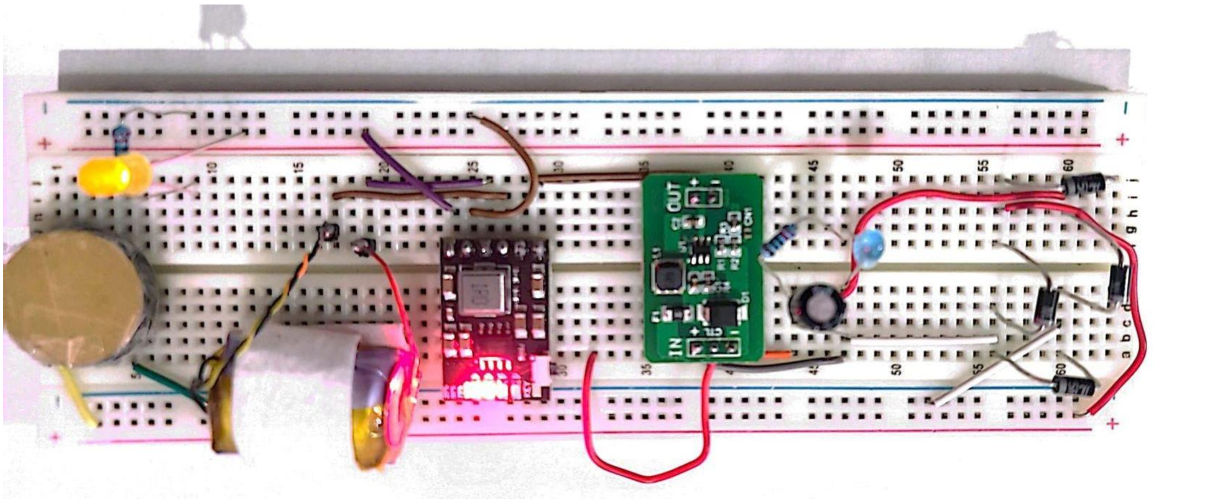


(Figure 17 - Working Final Release Energy Harvesting Circuit)

Comparative Analysis

Alpha Release:

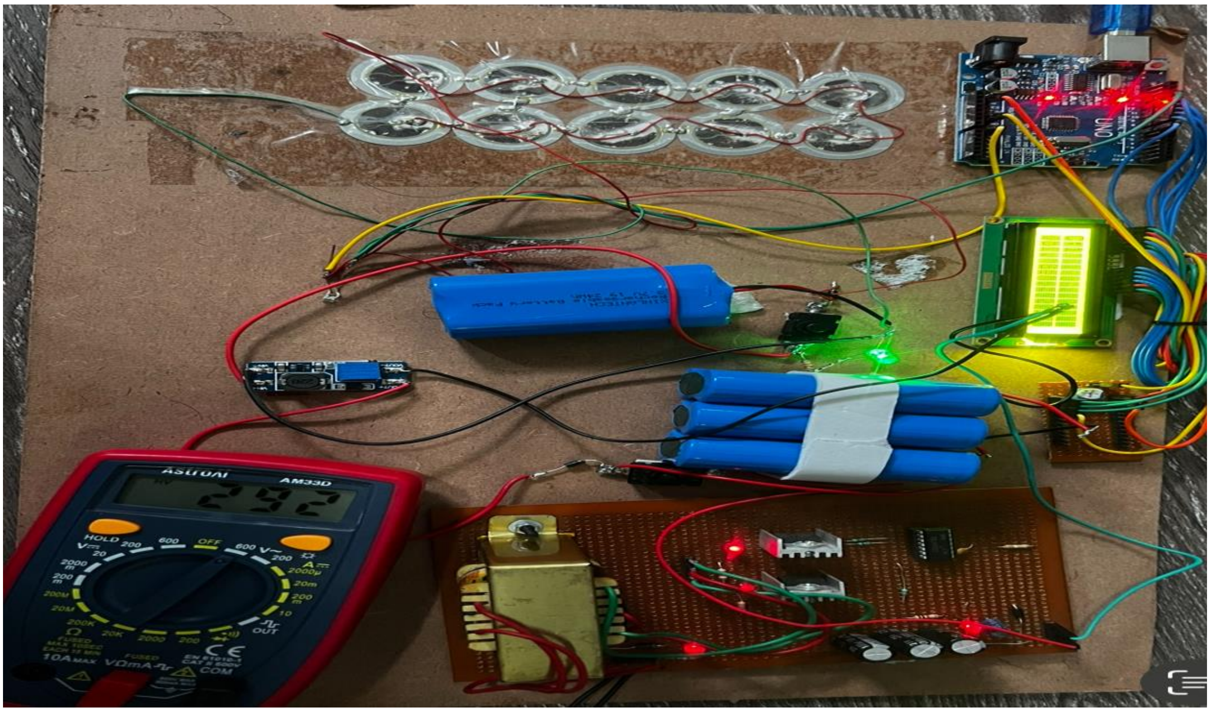
1. The alpha Release utilised piezo for energy generation but faced challenges due to inefficient voltage conversion and storage.
2. It relied on a basic voltage booster without optimization techniques, leading to suboptimal power output.
3. The charging mechanism with the Charging Circuit for rechargeable batteries lacked precision control, resulting in slower charging rates and potential energy loss
4. There was no inverter transformer circuit for AC conversion which only led to having a DC output.
5. Monitoring and control were rudimentary, lacking real-time feedback and comprehensive data logging.



(Figure 18 - Alpha Release)

Current System (Final Release):

1. The current system integrates advanced voltage optimization techniques with the use of a sophisticated voltage booster, enhancing power efficiency and output stability.
2. Charging mechanisms have been refined for faster and more precise charging of rechargeable batteries, minimising energy loss during the process with the help of Voltage Booster and diodes.
3. The inverter transformer circuit has been implemented for improved voltage regulation, ensuring a consistent and reliable 220V AC output suitable for a wide range of applications.
4. Monitoring and control capabilities have been significantly upgraded with the integration of Arduino UNO and Multimeter, providing real-time feedback on voltage levels and step counts for enhanced system management.



(Figure 19 - Final Release)

Key Technical Improvements:

Voltage Optimization: The current system employs advanced voltage optimization techniques, such as variable resistors and capacitor configurations, to achieve a steady and efficient voltage output.
Charging Precision: Charging mechanisms have been tuned for precise control over charging rates, improving overall energy storage and utilisation efficiency.
Inverter Circuit Redesign: The redesign of the inverter transformer circuit ensures stable and regulated AC output, addressing previous issues with voltage fluctuation and reliability.
Enhanced Monitoring and Control: Integration of Arduino UNO and Multimeter provides comprehensive monitoring and control capabilities, enabling real-time feedback and data logging for better system management.

By comparing these parameters across different systems, we get insights into the performance, capabilities, and suitability for specific applications. The table serves as a comprehensive reference to evaluate and contrast the key technical aspects of each system.

Parameters	Alpha Release	Final Release
Power Output	1.23 V (only one transducers used in first prototype)	238 AC V (Range 220 V - 250 V)
Efficiency	23.54%	76.67%
Lifecycle	80-100 Cycle	450-500 Cycle for the rechargeable batteries
Computational Resources	No such system was implemented	Arduino UNO (Atmega328P with 32KB Flash Memory , SRAM 2KB, Operating System 5V)

(Table 1 - Key Technical Parameters)

Hardware Components

1. **10 Piezoelectric Modules:** These modules are used to convert mechanical vibrations into electrical energy through the piezoelectric effect.
2. **4 Battery 3.7V each:** These batteries store the electrical energy generated by the piezoelectric modules.
3. **1 Voltage Booster:** The voltage booster is used to increase the voltage output
4. **DC to AC converter circuit:** This circuit converts the DC voltage output from the batteries into AC voltage
    - **IC CD4047:** It is used to generate the necessary timing signals for the DC to AC converter circuit.
    - **2 IRFZ44 Power MOSFET:**These MOSFETs act as switches to control the flow of electrical current in the system.

- **12-0-12/1A Secondary Transformer:** This transformer is used to step up or step down the voltage as required by the system.
- **22 KOhm Variable Resistor:** This variable resistor allows for precise adjustment of resistance in the circuit
- **2 100 Ohm/10w resistor:** These resistors are used to limit the flow of current in the circuit and protect components from damage due to excessive current.
- **0.22 uf Capacitor:** Capacitors are used to store and release electrical energy in the circuit.

5. **2 Switch:** Switches are used to manually control the flow of electricity in the circuit.
6. **MultiMeter:** A multimeter is used for measuring various electrical parameters such as voltage, current, and resistance.
7. **Wires for Connection:** These wires are used to connect various components of the system together.
8. **Arduino UNO:** It is used to control the operation of the system, read transducers data, and interface with other hardware components.
9. **16X2 LCD Screen:** It is used to show the voltage and footsteps.
10. **2 Capacitors:** Capacitors are used to store and release electrical energy in the circuit.
11. **1 KOhms resistor:** These resistors are used to limit the flow of current in the circuit.
12. **Light LED's:** To reflect the output of the circuit.
13. **2 Diodes - 1N4007:** These are used to allow the current to flow in one direction and also used for rectification purposes.
14. **Voltage Regulator 7805:** This voltage regulator regulates the input voltage to a stable output.
15. **Soldering Iron:** A soldering iron is used to join electrical components together by melting solder onto the connections.

Software Components and Online Resources Used

1. **LTspice:** To showcase the simulation of our system.
2. **Arduino IDE:** To write the code for Arduino UNO.
3. **Wokwi:** Simulation for Arduino UNO , LCD and .
4. **Pspice:** - Electric Simulation for our system.
5. **Tinkercad:** - CAD Model Designing.

Testing

Overview

The evolution of our energy harvesting system has been guided by rigorous testing at each stage of development. These tests were designed to assess the functionality and reliability of all system components, including piezo transducers, battery charging circuits, voltage boosters, inverters, Arduino UNO integration, and overall system integration and user interaction. Testing methodologies were consistent across various development phases, allowing for direct comparison of performance improvements.

Test Procedures and Equipment

The following tests were conducted using standard laboratory equipment such as multimeters, oscilloscopes, and manual inspection tools:

Test Category	Success Criteria
Piezo Transducers Output Test	Transducers must consistently generate voltage within the specified range of 2.68V - 3.02V under applied mechanical force.
Battery Charging and Voltage Boost Functionality	The battery must charge without exceeding or falling below the designated thresholds (3.7V - 4.2V). The voltage booster must output a stable voltage of approximately 11.4V.
Output Voltage and Inverter Functionality Test	The inverter must convert 11.1V DC to a stable 220V AC output. The frequency and waveform should meet system specifications without any significant distortion.
Complete System Integration Test	All components must work together seamlessly under normal operating conditions. The system should meet all final output specifications with no integration issues.
User Interaction and Safety Check	All user interface elements must be intuitive and function correctly. The system should be easy to operate without prior extensive training.

	Enclosures must be robust and protect internal components from routine handling and environmental factors.
Arduino UNO and LCD Functionality	The Arduino UNO must control the system accurately, with the LCD displaying real-time and correct voltage readings and step counts.

1. Piezo Transducers Output Test
Objective: Confirm that the piezo transducers generate the expected voltage when mechanical force is applied.
Equipment: Multimeter, Manual Force Application (e.g., pressing by hand)
Procedure:

- Manually apply a consistent force to the piezo transducers.
- Measure the output voltage using the multimeter.
- Verify the voltage is within the expected range.
- Repeat for multiple transducers to ensure consistent behavior across the system.

2. Battery Charging and Voltage Boost Functionality
Objective: Ensure the 3.7V battery charges correctly and that the voltage booster efficiently increases the voltage to 11.4V.
Equipment: Multimeter, Oscilloscope
Procedure:

- Connect the multimeter to the output of the piezo transducers and the input of the 3.7V battery to monitor charging voltage.
- Verify that the battery charges without exceeding or dropping below the designated thresholds.
- Use an oscilloscope to observe the voltage booster's output to ensure it is stable at approximately 11.4V.
- Check for any fluctuation or noise in the signal that could indicate instability.

3. Output Voltage and Inverter Functionality Test
Objective: Test the inverter circuit's ability to convert 11.1V DC to 220V AC effectively.
Equipment: Oscilloscope, Multimeter
Procedure:

- Measure the DC input to the inverter circuit with a multimeter to ensure it matches expected levels.
- Use the oscilloscope to check the AC output from the inverter transformer.
- Ensure the output is a stable AC waveform at 220V.
- Confirm the frequency and waveform quality meet system specifications.

4. Arduino UNO and LCD Functionality Test
Objective: Verify that the Arduino UNO controls the system as intended and that the LCD displays correct information.
Equipment: Visual Inspection, Manual Testing
Procedure:

- Power up the Arduino UNO and observe the boot-up sequence on the LCD.
- Check that the voltage readings and step count are displayed correctly on the LCD as changes occur in system operation.
- Manually change inputs where possible (e.g., varying the force on transducers) and monitor the LCD for real-time updates.

5. Complete System Integration Test
Objective: Ensure all components work together as a complete system and meet the final output specifications.
Equipment: Multimeter, Manual Inspection
Procedure:

- Simulate normal operating conditions by applying continuous force to the piezo transducers.
- Use a multimeter to check voltages at various stages (battery, voltage booster, inverter input).
- Use an oscilloscope to monitor the final AC output for stability and correct voltage.
- Perform a visual and manual inspection of all connections and components for signs of wear, poor connections, or potential failures.

6. User Interaction and Safety Check
Objective: Confirm that all user interfaces are intuitive and all safety measures are in place.
Equipment: Visual Inspection, Manual Testing
Procedure:

- Verify that all interface controls, including buttons and switches, operate smoothly and respond accurately to user inputs.
- Confirm that the system's design prevents exposure of internal components, even under conditions of regular wear and tear.
- Check that all housing and enclosures are robust, securely fastened, and effectively safeguard the internal components from mechanical damage and environmental exposure.

Test Results Summary

Test Category	Test Objective	Initial Release Results	Alpha Release Results	Final Release Results
Piezo Transducers Output Test	Verify correct voltage generation by piezo transducers.	Voltage very far below required range, in the range of 250-330mV	Voltage output improved to a peak of 1.23 V, but decays quickly.	Voltage consistently within target range (2.68V - 3.02V).
Battery Charging and Voltage Boost	Ensure the battery charges correctly and voltage booster functions properly.	Not enough input to the voltage booster. Not connected to the charging circuit.	Not enough input to the voltage booster. Not connected to the charging circuit.	Stable charging and boosting, with outputs at expected levels.
Output Voltage and Inverter Test	Test the effectiveness of the inverter circuit from DC to AC.	Only Observed in LTSpice simulation.	Very Low Voltage around 1.23 V DC was observed per one transducer.	Stable and correct AC waveform at 220V; meets all specs.
Arduino UNO and LCD Functionality	Ensure Arduino UNO controls and displays system stats accurately.	Not Applicable for this release	A rudimentary LED for visual feedback correctly indicated the presence of voltage, but no way to measure the level.	Accurate and real-time display of voltage generated as well as a step counter.

Complete System Integration Test	Confirm all components work seamlessly as a whole system.	Release failed at the power output level. Was not integrated with the remaining components.	Voltage Range from 1.3- 3.2 V DC was observed on multimeter	Seamless system operation with no integration issues.
User Interaction and Safety Check	Verify user interface intuitiveness and system safety.	Little room for user interaction. Passed safety checks	User interaction is straightforward, even though it's limited. Passed safety checks.	More intuitive interface, however, many internal components are exposed to the end user. Passed safety checks.

Sustainability and Unintended Consequence Analysis

Sustainability Analysis

Our project has evolved significantly across different releases, impacting its sustainability aspects in several ways. The primary positive impact lies in our approach to energy harvesting and efficiency. With the use of piezoelectric actuators and inverter transformer circuit, our system harnesses energy from ambient sources, providing a sustainable power solution for electronic devices. In the current release, we have optimised the energy conversion efficiency to ensure effective energy capture and utilisation, aligning with sustainability goals.

In terms of component selection, the inclusion of Schottky diodes in the rectification circuit, a decision made in the previous release, continues to contribute to efficiency and low power consumption. This choice reflects our commitment to selecting components with minimal environmental impact, considering factors such as production methods, materials, cost, and end-of-life disposal.

Our cost efficiency strategy, implemented in the current release, involves a combined configuration of actuators and modifications to minimise phase differences, ensuring optimal power output , without compromising reliability over the product lifecycle. This approach considers longevity and reliability to avoid increased maintenance requirements and overall costing impact.

Unintended Consequence Analysis

Throughout our project iterations, we have encountered unintended consequences that require careful consideration and mitigation strategies. One such challenge is interference between actuators, addressed in the current release by exploring individual rectifiers for series actuators to minimise interference and optimise performance and casing issue which might have not been able produce a good efficient output without proper modifications and redesign as there are lot of factors like water, dust thrust which needs to be considered.

Environmental impact considerations extend to component disposal, particularly capacitors, plastic waste and out of cycle rechargeable batteries which can contribute to electronic waste if not recycled properly. Our ongoing analysis involves assessing the environmental implications of component disposal to mitigate potential negative consequences.

Long-term reliability remains a focus, with considerations for capacitor and battery degradation, actuator wear and tear, and overall component lifespan to prevent system failures or increased maintenance needs.

Global component sourcing practices have also been reviewed to ensure responsible procurement and reduce environmental risks associated with manufacturing and supply chains.

In conclusion, our project showcases sustainability and efficiency improvements across releases, with ongoing analysis and mitigation strategies addressing unintended consequences. Regular updates based on evolving standards and technologies contribute to a robust, efficient, and impactful energy harvesting system.

MANAGEMENT VOLUME

As-built project schedule

Story point estimates:

Story point	Amount of effort required	Amount of time required	Task complexity	Task risk or uncertainty
1	Minimum effort	A few minutes	Little complexity	None
2	Minimum effort	A few hours	Little complexity	None
3	Mild effort	A day	Low complexity	Low
5	Moderate effort	A few days	Medium complexity	Moderate
8	Severe effort	A week	Medium complexity	Moderate
13	Maximum effort	A month	High complexity	High

(Figure 20 source: https://asana.com/resources/story-points)

User Stories – Story point estimate

1. As a user, I want to efficiently harness mechanical energy using piezo from the surroundings, so I can generate energy in a sustainable way - 3

   o Tasks involved:

   § Research and select optimal piezo for mechanical energy harvesting.

   § Develop and test prototypes for efficient energy conversion.

   § Design and implement circuitry for energy conditioning and storage.

§ Integrate the system into practical applications for real-world use.

§ Conduct field testing and iterate based on performance feedback.

2. As an engineer, I need to generate sufficient electrical power to meet energy demands at a small scale of portable applications – 8

- o Tasks involved:

  § Assess energy demands and requirements for various portable applications.

  § Identify suitable power generation technologies for small-scale applications.

  § Design and develop power generation systems tailored to portable use.

  § Implement efficient energy conversion and storage mechanisms.

  § Test and optimise power generation systems for reliability and performance.

3. As a researcher, I want a clear representation of the energy harvesting process to understand its efficiency and potential applications – 5

- o Tasks involved:

  § Review existing literature and research on energy harvesting processes.

  § Identify key factors influencing efficiency and potential applications.

  § Develop clear visual representations and models of energy harvesting processes.

  § Conduct simulations or experiments to validate representations.

  § Analyze results to gain insights into efficiency and application potentials.

4. As a system operator, I want an intuitive way to monitor the energy harvesting system’s performance and status to ensure optimal operation – 5

- o Tasks involved:

    - § Determine critical parameters for monitoring energy harvesting system performance.

    - § Design user-friendly interface for displaying system status and performance metrics.

    - § Develop real-time monitoring capabilities for immediate feedback.

    - § Implement alerts or notifications for abnormal system behaviour.

    - § Test monitoring interface for usability and effectiveness in ensuring optimal operation.

5. As a user of the energy harvesting system, I need a visual representation and controller to provide real-time monitoring and feedback on the energy harvesting process, including the number of steps taken (if applicable) and the force applied to the . – 5

- o Tasks involved:

    - § Design a visual representation and controller for real-time monitoring of the energy harvesting process.

    - § Incorporate to measure the number of steps (if applicable) and force applied to .

    - § Develop interface for providing feedback on energy generation performance.

    - § Ensure user-friendliness and intuitive operation of the monitoring system.

    - § Test the visual representation and controller for accuracy and effectiveness in providing real-time feedback.

6. As a user of renewable energy systems, I need a high-capacity battery to efficiently store the harvested electrical energy for later use when energy generation is low - 3

- o Tasks involved:

    - § Assess energy storage requirements for renewable energy systems.

§ Research and select high-capacity battery technologies suitable for energy storage.

§ Design battery system for efficient storage and retrieval of harvested electrical energy.

§ Implement charging and discharging mechanisms to optimise battery performance.

§ Test the battery system for reliability and longevity in storing harvested energy.

7. As a renewable energy system designer, I want to increase the number of Piezoelectric efficiently converting mechanical energy from ambient vibrations and direct force into electrical power, to generate a sufficient amount of energy - 3

o Tasks involved:

§ Evaluate current efficiency of piezoelectric in converting mechanical energy.

§ Research methods to increase efficiency of piezoelectric .

§ Design and implement strategies to optimise placement and utilisation of .

§ Test and iterate designs to maximise energy generation from ambient vibrations and direct force.

§ Ensure scalability and reliability of increased transducer efficiency for energy generation.

8. As a developer of the energy harvesting system's electronics, I require a battery charging circuit that includes a boost converter to elevate the voltage output from piezoelectric for efficient charging of a high-capacity battery - 8

o Tasks involved:

§ Define requirements for battery charging circuit with boost converter.

§ Design circuit layout and components for efficient voltage elevation from piezoelectric .

§ Develop control mechanisms for regulating the charging process and battery protection.

§ Prototype and test the battery charging circuit for compatibility and efficiency.

§ Iterate and optimise circuit design based on performance testing and feedback.

9. As a consumer of renewable energy solutions, I rely on a high-capacity battery to store harvested electrical energy efficiently for later use, providing reliable energy storage solutions for extended periods - 5

- o Tasks involved:

  § Assess energy storage requirements for extended periods.

  § Research and select high-capacity battery solutions suitable for reliable energy storage.

  § Design battery system for efficient storage and retrieval of harvested electrical energy.

  § Implement charging and discharging mechanisms to optimise battery performance.

  § Test the battery system for reliability and longevity in providing uninterrupted energy storage.

10. As a consumer relying on renewable energy sources, I expect the batteries to power my applications reliably for extended periods, ensuring uninterrupted operation - 3

- o Tasks involved:

  § Define requirements for reliable power supply from renewable energy batteries.

  § Research and select battery technologies capable of providing uninterrupted power for extended periods.

  § Design battery systems tailored for consistent and reliable power delivery.

  § Implement monitoring and management systems to ensure uninterrupted operation.

  § Test battery systems for reliability and longevity in powering applications for extended durations.

11. As a user of devices requiring elevated voltage levels, I require circuitry to convert stored electrical energy into higher output voltage (210 to 220 volts) to meet the device specifications – 8

- o Tasks involved:
  - § Define voltage conversion requirements to meet device specifications.
  - § Research and select appropriate circuitry components for voltage elevation.
  - § Design circuit layout and configuration for converting stored electrical energy to higher output voltage.
  - § Develop control mechanisms for regulating voltage output within specified range.
  - § Test and optimise circuitry design for efficiency and compatibility with devices.

12. As an engineer designing electrical systems, I need the power output to be regulated within specified ranges consistently to ensure compatibility with various devices - 5

- o Tasks involved:
  - § Define power output specifications and ranges for compatibility with devices.
  - § Research and select voltage regulation mechanisms suitable for electrical systems.
  - § Design power regulation circuitry to maintain consistent output within specified ranges.
  - § Implement monitoring and feedback mechanisms to ensure regulation accuracy.
  - § Test and validate power output regulation for compatibility with various devices.

13. As a user operating in diverse environments, I expect the energy harvesting system to exhibit robustness and durability, capable of withstanding environmental conditions and operational stresses - 5

- o Tasks involved:

§ Identify environmental conditions and operational stresses the system will encounter.

§ Research and select components known for robustness and durability.

§ Design system architecture to withstand diverse environments and stresses.

§ Implement protective measures and ruggedization techniques as needed.

§ Test the energy harvesting system under various conditions to ensure robustness and durability.

14. As a maintenance technician, I appreciate components selected and integrated for long-term reliability, minimising maintenance requirements and ensuring consistent performance - 5

o Tasks involved:

§ Assess components for long-term reliability and maintenance requirements.

§ Select and integrate components known for durability and longevity.

§ Design system with accessible components for easy maintenance and replacement.

§ Implement preventive maintenance measures to extend component lifespan.

§ Test system components and maintenance procedures to ensure consistent performance and minimise downtime.

15. As a planner for energy infrastructure, I require the system to be scalable to accommodate varying power generation requirements and environmental conditions - 8

o Tasks involved:

§ Define scalability requirements for accommodating varying power generation needs.

§ Research scalable energy infrastructure designs and technologies.

§ Design modular system architecture to accommodate expansion or contraction.

§ Implement monitoring and control mechanisms for scaling system capacity.

§ Test scalability features under different power generation requirements and environmental conditions.

16. As an integrator of energy solutions, I value the flexibility to adapt the system to different applications and scenarios with modular and customizable features - 8

o Tasks involved:

§ Identify different applications and scenarios for energy solution integration.

§ Research modular and customizable features for energy system components.

§ Design system with interchangeable modules for adaptability.

§ Implement plug-and-play interfaces for easy integration into various applications.

§ Test system flexibility and customization features for compatibility and usability in different scenarios.

17. As a regulator ensuring safety standards compliance, I expect adherence to relevant safety standards and regulations to ensure user and environmental safety - 5

o Tasks involved:

§ Identify relevant safety standards and regulations for energy systems.

§ Ensure design and implementation adhere to safety standards and regulations.

§ Conduct safety assessments and certifications as required.

§ Develop documentation and procedures for maintaining safety compliance.

§ Regularly review and update safety measures to ensure ongoing compliance.

18. As an installer of energy systems, I prefer a system that is easy to install and integrate into existing infrastructure or applications, minimising installation time and complexity - 5

- o Tasks involved:

  - § Assess existing infrastructure and installation requirements.

  - § Design system components for compatibility and ease of installation.

  - § Develop installation procedures and guidelines for installers.

  - § Provide training and support for smooth integration into existing infrastructure.

  - § Test installation process for efficiency and minimise complexity.

19. As a business owner reliant on energy systems, I aim to minimise downtime for maintenance to ensure continuous operation and productivity - 3

- o Tasks involved:

  - § Identify maintenance requirements and intervals for energy systems.

  - § Implement preventive maintenance measures to minimise downtime.

  - § Design system components for easy maintenance and accessibility.

  - § Develop maintenance schedules and procedures for timely servicing.

  - § Monitor system performance and conduct proactive maintenance to prevent unexpected downtime.

20. As a decision-maker evaluating energy solutions, I seek a cost-effective solution that balances initial investment with long-term benefits and return on investment - 3

- o Tasks involved:

  - § Analyze initial investment costs and long-term benefits of energy solutions.

  - § Research cost-effective technologies and implementation strategies.

§ Conduct cost-benefit analysis to assess return on investment.

§ Evaluate potential savings and efficiencies gained over the system's lifecycle.

§ Make decisions based on the balance of initial costs and long-term benefits.

21. As a financial analyst, I consider maintenance, operation, and lifecycle costs over the system's expected lifespan to assess its overall economic viability and sustainability - 3

o Tasks involved:

§ Gather data on maintenance, operation, and lifecycle costs of energy systems.

§ Analyze costs over the system's expected lifespan to determine economic viability.

§ Consider factors such as depreciation, energy savings, and potential revenue streams.

§ Evaluate sustainability metrics alongside economic considerations.

§ Provide recommendations based on the overall economic viability and sustainability of the energy solution.

NOTE: In the spirit of the Agile methodology, it might be observed that some tasks appear multiple times across different user stories above. This redundancy is a deliberate aspect of our iterative process, allowing us to address diverse user needs and system requirements from various angles. Embracing redundancy in this context enhances our adaptability and responsiveness to evolving project dynamics. It underscores our commitment to delivering comprehensive solutions and continually refining our approach based on feedback and insights gained throughout the project management cycle.

Final Work Breakdown Structure

Note: All the tasks below have been a collaborative effort from the group. We made sure that a minimum of 3-4 people were working simultaneously per week on the project since there were times where not all of us could afford to give time.

Updates till this point:

- We finished ideating the potential solution that we needed, open to changes along the way

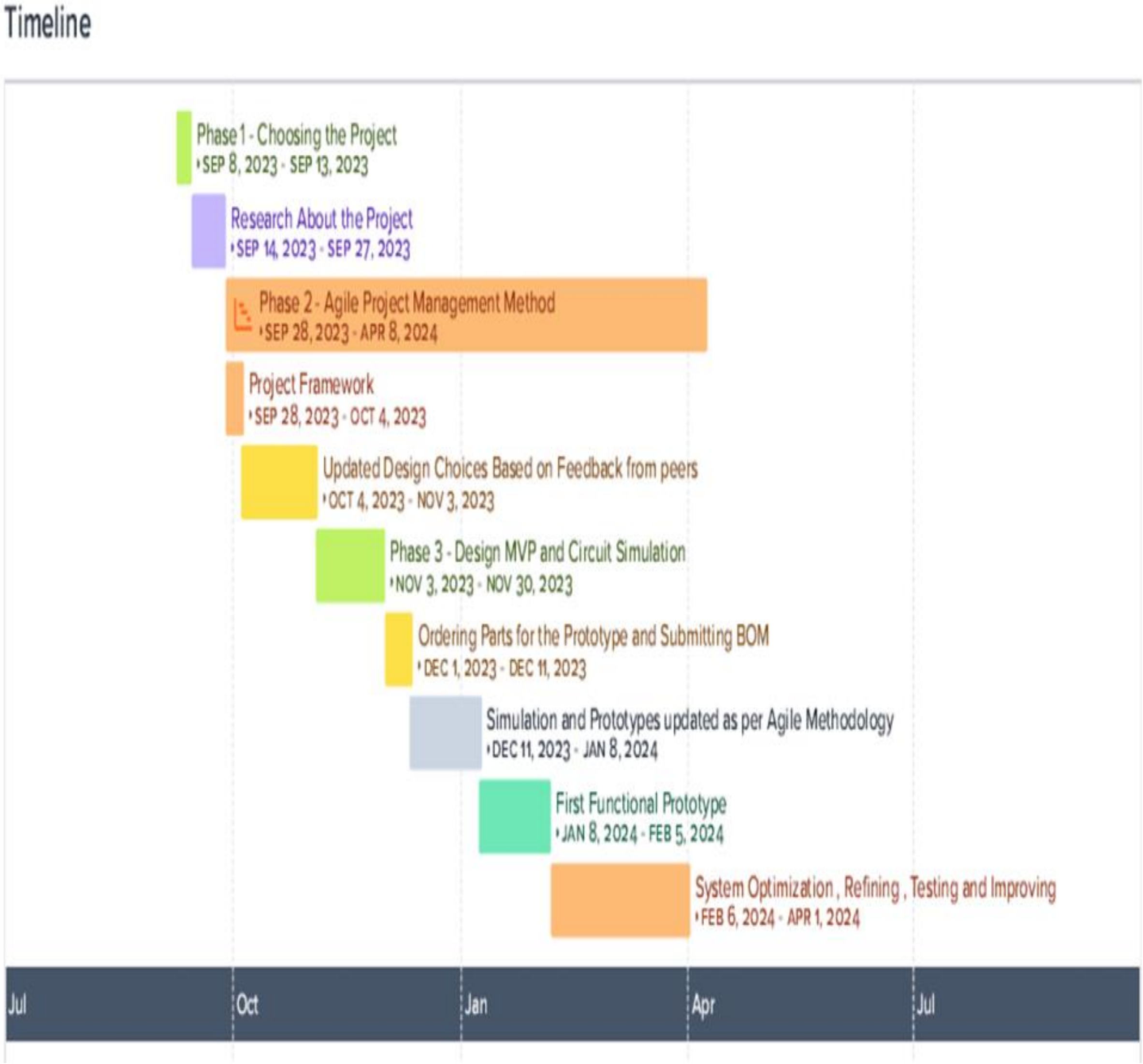
- We tried to think about the different ways we can pivot along the way for every problem that we might encounter

- We've had multiple meetings with regards to the project goal with Prof. Mokhtar Aboelaze, our project supervisor

- We looked out for vendors that sell the tools and components that we needed at a cheap price

- Drafted an overall timeline for the whole project for the foreseeable future (Figure below)

Drafted overall timeline: (Note: this was the previous timeline made which was still subject to changes)



(Figure 21 - Agile Timeline)

SEP 8, 2023 - SEP 13, 2023	Choosing the Project either from list or defining a sustainable solution from the list of 16 UN Sustainable Goals
Research About the Project SEP 14, 2023 - SEP 27, 2023	Understanding the project, conducting research, and defining the problem to effectively design a complex product, service or process using the engineering design process.
Phase 2 - Agile Project Management Method SEP 28, 2023 - APR 8, 2024	Choosing the style of Project Management method for our project
Project Framework SEP 28, 2023 - OCT 4, 2023	talk about project's problem definition, requirements, stakeholder/customer analysis, the decided project charter, Team member's involvement, roles and responsibilities
Updated Design Choices Based on Feedback from peers OCT 4, 2023 - NOV 3, 2023	update on design choices, talk about general update and pragmatic approaches, articulate the aspect of the project that you would like your peers to provide a feedback, in a clear manner.
Phase 3 - Design MVP and Circuit Simulation NOV 3, 2023 - NOV 30, 2023	develop a potential prototype to effectively design a complex product, service or process using the engineering design process.
Ordering Parts for the Prototype and Submitting BOM DEC 1, 2023 - DEC 11, 2023	All Parts Arrive: In this phase, our focus is on ensuring we have all of the required components and necessary materials for the subsequent stages of the project.
Simulation and Prototypes updated as per Agile Methodology DEC 11, 2023 - JAN 8, 2024	During this period, our attention shifts towards refining the simulation. We identify and address any discrepancies or uncertainties in the simulation, ensuring that our theoretical groundwork is solid before progressing to the physical implementation.
First Functional Prototype JAN 8, 2024 - FEB 5, 2024	This marks a pivotal stage where we transition from theory to practice. We aim to build our initial functional prototype, integrating the theoretical insights gained from the simulation phase into a tangible model that demonstrates the viability of harvesting energy from piezo sensors to power security cameras. Simultaneously, a subgroup team tackles the challenge of modularity, ensuring that our design allows for flexibility and scalability in different scenarios
System Optimization , Refining , Testing and Improving FEB 6, 2024 - APR 1, 2024	System Optimization and Presentation: In this final stretch, the team focuses on refining the system, addressing any gaps, and making minor improvements. This phase involves thorough testing and troubleshooting. Our goal is to optimise the overall performance, making the project more seamless and presentable.

(Figure 22 - Continued Timeline with Deadlines and Tasks)

(Figure 23 - Final Timeline of tasks and objectives)

Designing a Minimum Viable Product Phase Sprints

Sprint 1 (Nov. 13 – Nov. 24)	
User story # worked on	1, 3, 6, 7
Other tasks involved	· Literature review · Stand-ups · Meeting with Prof. Mokhtar (project supervisor) · Research on the various hardware components that might be of use to our project · Started playing around with the LTSpice simulation to see how much energy we can generate
Sprint notes	· Last 2 days were allocated for sprint planning for the next sprint · We approached a dead-end on the problem of generating just a small amount of energy, so we approached Prof. Mokhtar (project supervisor), and Prof. Franz (ENG4000 instructor) seeking for feedback
Backlog items	· Search for a cheap source to get our required hardware components from · Create an LTSpice simulation of a circuit to simulate the amount of energy that can be generated
Total # of hours worked (collaborative effort) Note: the number is equal to the total # of people who worked multiplied by the # of hours each person worked	· 7 people x 10 hours each = 70 hours

Sprint 2 (Nov 27 – Dec. 8)	
User story # worked on	19, 20, 21
Other tasks involved	· Literature review · Stand-ups · Meeting with Prof. Mokhtar (project supervisor) · Research on alternative various hardware components that we can use · Created the LTSpice simulation to simulate the amount of energy that can be generated with the components used · Search for a cheap source to get our required hardware components from · Compiled our progress into the midterm report · Order the required hardware components that we need
Sprint notes	· Last 2 days were allocated for sprint planning for the next sprint · Found out that we can use a voltage booster to enhance the amount of voltage generated
Backlog items	· Development of the circuit
Total # of hours worked (collaborative effort) Note: the number is equal to the total # of people who worked multiplied by the # of hours each person worked	· 5 people x 10 hours each = 50 hours

Alpha Release Phase Sprints

Sprint 3 (Jan. 8 – Jan. 19)	
User story # worked on	2, 5, 10
Other tasks involved	· Literature review · Stand-ups · Meeting with Prof. Mokhtar (project supervisor) · Started the development of the circuit using the various components
Sprint notes	· Last 2 days were allocated for sprint planning for the next sprint · The breadboard shorted because of an accidental connection that was made
Backlog items	· Order the parts again due to the shortage of components after the short circuit that occurred · Development of the circuit · Regression testing using an oscilloscope to get an idea about the amount of voltage that was being generated, and to ensure everything works as expected after any modifications
Total # of hours worked (collaborative effort) Note: the number is equal to the total # of people who worked multiplied by the # of hours each person worked	· 7 people x 5 hours each = 35 hours

Sprint 4 (Jan. 22 – Feb. 2)	
User story # worked on	12, 13
Other tasks involved	· Stand-ups · Meeting with Prof. Mokhtar (project supervisor) · Integrated the voltage booster into the whole project to increase the voltage from 3.7V to 11V · Reordered some components that were affected · Development of the circuit to enhance the amount of energy we were generating · Rigorous regression testing by using an Oscilloscope to get an idea about the amount of energy that was being generated, and to ensure that everything still works as expected after integrating the voltage booster
Sprint notes	· Last 2 days were allocated for sprint planning for the next sprint · Found out that we can also use an inverter transformer circuit to convert the 11.1V DC output into 220V AC

Backlog items	· Further development of the circuit to enhance the amount of energy that was being generated · Rigorous regression testing of the circuit developed using an oscilloscope to get a visual representation of the amount of energy that was being generated, and to ensure that everything still works as expected after any modifications · Integrate the battery that was to be charged using the energy generated from the piezo
Total # of hours worked (collaborative effort) Note: the number is equal to the total # of people who worked multiplied by the # of hours each person worked	· 7 people x 15 hours each = 105 hours

Sprint 5 – Short Sprint (Feb. 5 – Feb. 9)	
User story # worked on	14, 18, 21
Other tasks involved	· Stand-ups · Meeting with Prof. Mokhtar (project supervisor) · Integrated the battery that was to be charged using the energy generated from the piezo · Further development of the circuit · Rigorous regression testing of the circuit developed using an oscilloscope to get a visual representation of the amount of energy that was being generated, and to ensure that

	everything still works as expected after integrating the battery
Sprint notes	· Last 2 days were allocated for sprint planning for the next sprint · Decided to integrate an LED screen with Arduino UNO and a multimeter to display the voltage generated, and the number of footsteps from the piezo
Backlog items	· Further development of the circuit · Rigorous regression testing of all the components present and connected to ensure everything still works as expected after any modifications · Integrate an inverter transformer circuit to convert the 11.1V DC output into 220V AC
Total # of hours worked (collaborative effort) Note: the number is equal to the total # of people who worked multiplied by the # of hours each person worked	· 7 people x 5 hours each = 35 hours

Beta Release Phase Sprints

Sprint 6 (Feb. 12 – Feb. 23)	
User story # worked on	4, 8, 9, 16, 18, 19
Other tasks involved	· Stand-ups · Meeting with Prof. Mokhtar (project supervisor) · Started drafting progress report 2 · Integrated an inverter transformer circuit to convert the 11.1V DC output into 220V AC · Further development of the circuit · Rigorous regression testing of the circuit developed using an oscilloscope to get a visual representation of the amount of energy that was being generated
Sprint notes	· Last 2 days were allocated for sprint planning for the next sprint
Backlog items	· Further development of the project by connecting a screen that displays something to show the amount of voltage · Rigorous regression testing of every connected component to make sure everything works as expected after connecting the inverter transformer · Integrate an LED screen with Arduino UNO and a multimeter to display the voltage generated, and the number of footsteps from the piezo

Total # of hours worked (collaborative effort) Note: the number is equal to the total # of people who worked multiplied by the # of hours each person worked	· 7 people x 15 hours each = 105 hours

Sprint 7 (Feb. 26 – March 8)	
User story # worked on	11, 15, 17, 19
Other tasks involved	· Stand-ups · Meeting with Prof. Mokhtar (project supervisor) · Compiled all progress into the progress report 2 · Integrated an LED screen with Arduino UNO and a multimeter to display the voltage generated, and the number of footsteps from the piezo
Sprint notes	· Last 2 days were allocated for sprint planning for the next sprint · Connecting the LED screen to the whole setup was a huge challenge
Backlog items	· Rigorous regression testing to ensure everything still works as expected after any modifications
Total # of hours worked (collaborative effort) Note: the number is equal to the total # of people who worked multiplied by the # of hours each person worked	· 7 people x 15 hours each = 105 hours

Sprint 8 – Short Sprint (March 11 – March 15)	
User story # worked on	· N/A
Other tasks involved	· Stand-ups · Meeting with Prof. Mokhtar (project supervisor) · Rigorous regression testing to ensure everything still works as expected after integrating the LED screen
Sprint notes	· Last 2 days were allocated for sprint planning for the next sprint · Not a lot of tasks were done on this short sprint due to the amount of other course load the team had
Backlog items	· Rigorous regression testing to ensure everything still works as expected after any modifications
Total # of hours worked (collaborative effort) Note: the number is equal to the total # of people who worked multiplied by the # of hours each person worked	· 4 people x 3 hours each = 12 hours

Final Release Phase Sprints

Sprint 9 (March 18 – March 29)	
User story # worked on	· N/A

Other tasks involved	· Stand-ups · Meeting with Prof. Mokhtar (project supervisor) · Rigorous regression testing to ensure that every component works as expected after any modifications · Tried to look for gaps in our project or aspects it can still be improved upon · Started drafting the final project report
Sprint notes	· Last 2 days were allocated for sprint planning for the next sprint
Backlog items	· Rigorous regression testing of every connected component to ensure that everything works as expected after any modifications · Making the project look better and more presentable for capstone day
Total # of hours worked (collaborative effort) Note: the number is equal to the total # of people who worked multiplied by the # of hours each person worked	· 7 people x 10 hours each = 70 hours

Sprint 10 (April 1 – April 12)	
User story # worked on	· N/A

Other tasks involved	· Stand-ups · Meeting with Prof. Mokhtar (project supervisor) · Compiled our progress into our final report for the project · Rigorous regression testing of every connected component to ensure that everything works as expected · Made the project look better, clean, and more presentable for capstone day
Sprint notes	· Made the project look cleaner and more presentable for capstone day · Developed and completed the final report for the whole project
Backlog items	N/A
Total # of hours worked (collaborative effort) Note: the number is equal to the total # of people who worked multiplied by the # of hours each person worked	· 7 people x 10 hours each = 70 hours

Resource Allocation Matrix per sprint

Sprint 1 (Nov. 13 – Nov. 24)			
Group members	Total # of hrs.	Individual tasks	Group tasks
Prabhkirat	10	Research on hardware components and alternatives	· Stand-ups

Rajat	10	LTSpice simulation	· Meeting with Prof. Mokhtar · User stories # 1, 3, 6, 7 · Approached Prof. Mokhtar and Prof. Franz for feedback · Literature review · Sprint planning for the next sprint
Ahmed	10	LTSpice simulation	
Saksham	10	LTSpice simulation	
Navraj	10	Research on hardware components and alternatives	
Jeet	10	Research on hardware components and alternatives	
Gaurav	10	Research on hardware components and alternatives	

Sprint 2 (Nov. 27 – Dec. 8)			
Group members	Total # of hrs.	Individual tasks	Group tasks
Prabhkirat	10	Research on hardware components and alternatives that can be used to improve the project	· Stand-ups · Meeting with Prof. Mokhtar · User stories # 19, 20, 21 · Literature review · Compiled progress into midterm report · Order the required components · Sprint planning for the next sprint
Rajat	10	LTSpice simulation	
Ahmed	0	N/A	
Saksham	10	LTSpice simulation	
Navraj	0	N/A	
Jeet	10	LTSpice simulation	

Gaurav	10	Research on hardware components and alternatives that can be used to improve the project	

Sprint 3 (Jan. 8 – Jan. 19)			
Group members	Total # of hrs.	Individual tasks	Group tasks
Prabhkirat	5	Improvements on LTSpice simulation	· Stand-ups · Meeting with Prof. Mokhtar · Literature review · User stories # 2, 5, 10 · Started the circuit development · Sprint planning for the next sprint
Rajat	5	Improvements on LTSpice simulation	
Ahmed	5	Development of the circuit	
Saksham	5	Development of the circuit	
Navraj	5	Improvements on LTSpice simulation	
Jeet	5	Development of the circuit	
Gaurav	5	Improvements on LTSpice simulation	

Sprint 4 (Jan. 22 – Feb. 2)			
Group members	Total # of hrs.	Individual tasks	Group tasks
Prabhkirat	15	Regression testing	· Stand-ups
Rajat	15	Regression testing	

Ahmed	15	Research on how to improve the amount of voltage generated	· Meeting with Prof. Mokhtar · User stories # 12, 13 · Reordered some components that were affected · Integrated the voltage booster to the project · Sprint planning for the next sprint
Saksham	15	Development of the circuit	
Navraj	15	Research on how to improve the amount of voltage generated	
Jeet	15	Development of the circuit	
Gaurav	15	Regression testing	

Sprint 5 (Feb. 5 – Feb. 9) – Short Sprint			
Group members	Total # of hrs.	Individual tasks	Group tasks
Prabhkirat	5	Regression testing	· Stand-ups · Meeting with Prof. Mokhtar · User stories # 14, 18, 21 · Integrated the battery to the project · Sprint planning for the next sprint
Rajat	5	Regression testing	
Ahmed	5	Research on how to further improve the amount of voltage generated	
Saksham	5	Development of the circuit	
Navraj	5	Research on how to further improve the amount of voltage generated	
Jeet	5	Development of the circuit	

Gaurav	5	Research on how to further improve the amount of voltage generated	

Sprint 6 (Feb. 12 – Feb. 23)			
Group members	Total # of hrs.	Individual tasks	Group tasks
Prabhkirat	5	Regression testing	· Stand-ups · Meeting with Prof. Mokhtar ·User stories # 4, 8, 9, 16, 18, 19 ·Started the progress report 2 draft ·Integrated the inverter transformer circuit · Sprint planning for the next sprint
Rajat	5	Regression testing	
Ahmed	5	Development of the circuit	
Saksham	5	Development of the circuit	
Navraj	5	Research on integrating an LED screen with Arduino UNO to the whole project	
Jeet	5	Development of the circuit	
Gaurav	5	Research on integrating an LED screen with Arduino UNO to the whole project	

Sprint 7 (Feb. 26 – March 8)			
Group members	Total # of hrs.	Individual tasks	Group tasks
Prabhkirat	15	Regression testing	· Stand-ups

Rajat	15	Regression testing	· Meeting with Prof. Mokhtar · User stories # 11, 15, 17, 19 · Compiled all progress into progress report 2 · Integrated the LED screen with Arduino UNO and multimeter to the project · Sprint planning for the next sprint
Ahmed	15	Development	
Saksham	15	Development	
Navraj	15	Development	
Jeet	15	Development	
Gaurav	15	Regression testing	

Sprint 8 (March 11 – March 15) – Short sprint			
Group members	Total # of hrs.	Individual tasks	Group tasks
Prabhkirat	0	N/A	· Stand-ups · Meeting with Prof. Mokhtar · Sprint planning for the next sprint
Rajat	0	N/A	
Ahmed	3	Regression testing	
Saksham	3	Development	
Navraj	3	Regression testing	
Jeet	3	Development	
Gaurav	0	N/A	

Sprint 9 (March 18 – March 29)			
Group members	Total # of hrs.	Individual tasks	Group tasks
Prabhkirat	10	Regression testing	· Stand-ups · Meeting with Prof. Mokhtar · Started drafting the final project report · Tried to look for gaps and aspects that the project can be improved upon ·Sprint planning for the next sprint
Rajat	10	Regression testing	
Ahmed	10	Development (Improvements)	
Saksham	10	Development (Improvements)	
Navraj	10	Regression testing	
Jeet	10	Development (Improvements)	
Gaurav	10	Regression testing	

Sprint 10 (April 1 – April 12)			
Group members	Total # of hrs.	Individual tasks	Group tasks
Prabhkirat	10	N/A	· Stand-ups · Meeting with Prof. Mokhtar · Compiled all progress into the final project report · Make the project look better, cleaner, and more presentable for capstone day
Rajat	10	N/A	
Ahmed	10	N/A	
Saksham	10	N/A	
Navraj	10	N/A	
Jeet	10	N/A	

Gaurav	10	N/A	

Project Procurement

Budget

Throughout the project lifecycle, meticulous tracking and monitoring of budget allocations, equipment procurement, and scheduling were paramount to ensure the successful implementation of our objectives. A detailed breakdown of project expenses reveals a total expenditure of $263.28, encompassing the essential components such as piezoelectric modules, batteries, voltage boosters, and various electronic components. Additionally, key equipment, including an oscilloscope and waveform generator, were borrowed from the labs to facilitate testing and validation processes. All purchased equipment and materials have been seamlessly integrated into the project system, contributing to its functionality and performance. No specific travel was required for this project, thereby minimising additional costs and streamlining resource utilisation.

Equipments	Quantities	Price
Piezoelectric Modules	10	$10.99
Battery 3.7V each	4	$120
Voltage Booster	1	$3.16
IC CD4047	1	$1.25
IRFZ44 Power MOSFET	2	$3
12-0-12/1A Secondary Transformer	1	$16
22 KOhm Variable Resistor	1	$0.80
100 Ohm/10w resistor	2	$1.60
0.22 uf Capacitor	1	$0.50
Switch	2	$4
MultiMeter	1	$21
Wires for Connection	Many	$10
Arduino UNO	1	$32
LED Screen	1	$8
Capacitors	2	$1
1 KOhms resistor	1	$0.80
LED	Many	$2
Diodes - 1N4007	2	$0.18
Voltage Regulator 7805	1	$1
Soldering Iron	1	$26
Oscilloscope	1	Loan
Waveform Genrator	1	Loan

(Table 2 - Budget)

Total = $263.28

Preliminary business case

The design problem addresses the growing demand for autonomous power solutions, where wired power systems often prove impractical. In response, our solution creatively utilises piezoelectric to harness ambient mechanical vibrations as a renewable energy source.

This as-built system presents an innovative approach to renewable energy harvesting, offering a sustainable solution to meet the needs of stakeholders across various industries. By converting mechanical energy into electrical power, the system caters to the demand for reliable and autonomous energy sources. Its versatility enables applications in diverse scenarios, ranging from remote transducers networks to wearable technology.

Preliminary Cost-Benefit Analysis:

- Initial investments in component procurement and system development are necessary but yield long-term benefits.
- Despite the initial costs, the system's ability to generate renewable energy from ambient mechanical vibrations reduces reliance on traditional power sources such as fossil fuels or grid electricity. Over time, this reduced dependence on traditional power sources can lead to significant cost savings, as the system provides a sustainable and potentially cheaper alternative for powering devices.
- The initial setup costs may be mitigated by the system's longevity and the reduction in ongoing operational expenses.

Strengths of the system:

- The system effectively harnesses renewable energy, contributing to sustainability goals and reducing carbon footprint.
- The system’s scalability allows for mass production, catering to diverse applications and markets, enhancing its economic viability and potential for widespread adoption.
- Traditional power sources such as fossil fuels and grid electricity are often subject to disruptions and vulnerabilities, such as supply shortages, price fluctuations, and infrastructure failures. Our system's ability to provide an alternative, autonomous power source reduces dependence on these traditional sources, enhancing energy independence and resilience for users, particularly in remote or off-grid locations where access to reliable electricity may be limited.

Weaknesses and Areas of Improvement:

- The initial investment required to procure components and set up the system may be prohibitive for certain stakeholders.
- To address this weakness, strategies such as offering financing options, subsidies, or incentives may be necessary to make the system more affordable and accessible to a broader range of users.
- While the system effectively harnesses renewable energy, its energy output may be limited in certain scenarios, such as environments with low mechanical vibrations or high energy demand.

- To improve the system's effectiveness, further optimization and innovation are needed to enhance energy conversion efficiency and output, ensuring that it can meet the requirements of a wider range of applications and users.

- If components of the system break or require repair, the process of identifying the issue, sourcing replacement parts, and performing repairs may be time-consuming and labour-intensive. This could potentially result in downtime and disruption to operations, particularly in critical applications where uninterrupted power supply is essential.

- To mitigate this weakness, efforts should be made to design the system with modular components and standardised parts to simplify repair and maintenance procedures. Additionally, establishing a robust support and servicing infrastructure can help expedite the resolution of issues and minimise downtime.

Opportunities for Market Penetration and Expansion:

- Industries increasingly prioritise sustainable energy solutions, creating a favourable market environment for the adoption of the system.
- With the proliferation of IoT technologies, there is a growing demand for autonomous power sources, presenting opportunities for market expansion and diversification.

Threats and Challenges:

- Competition from alternative energy technologies or traditional power sources may pose challenges to market penetration and differentiation.
- Regulatory hurdles or standards compliance requirements could affect product development and market entry strategies. Failure to meet regulatory requirements can result in legal penalties, delays in market entry, and damage to reputation, posing significant challenges to the commercial success of the system.

Technical Risks:

- Voltage Instability: There is a risk of voltage instability in the system, leading to inconsistent power output and potential damage to connected devices. Mitigation: Implement voltage regulation mechanisms and conduct thorough testing to ensure stability under varying load conditions.
- Component Failure: Components such as the voltage booster or inverter transformer may fail during operation, resulting in system downtime and reduced functionality. Mitigation: Use high-quality, reliable components, implement redundancy where possible, and have contingency plans for quick replacement or repair.

LESSONS LEARNED VOLUME

Deviations from plan

Throughout the project lifecycle, several valuable lessons were learned, particularly from significant deviations from the design plan. These deviations provided insights into both the strengths and limitations of the solution, as well as recommendations for possible improvements in future iterations.

Reflecting on these deviations, it became evident that proactive risk management and continuous monitoring are essential for anticipating and mitigating potential challenges. Furthermore, effective communication and collaboration among team members played a crucial role in identifying and addressing issues promptly. By embracing a mindset of continuous improvement and learning from both successes and setbacks, the project team gained valuable experience and expertise that will inform future projects and endeavours.

Voltage Conversion and Storage Challenges:

Challenge: In the alpha release, inefficient voltage conversion and storage methods were observed, leading to suboptimal power efficiency. These inefficiencies resulted in fluctuations in voltage output and reduced energy storage capacity, impacting the overall performance of the system.
Lesson Learned: The inefficiencies we encountered showed us how important it is to make the process of converting and storing electrical power more efficient. This means we need to find ways to make sure we're using the right parts and putting them together in the best way possible. We realised that we need to be really careful about picking the parts we use, how we set up the circuits, and how everything fits together in the system.
How we solved the challenge: We implement advanced voltage optimization techniques, such as variable resistors and capacitor configurations, to achieve a more stable and efficient voltage output

Charging Mechanism Precision and Efficiency:

Challenge: In our initial design, we noticed that the charging process for our batteries wasn't very precise. This meant that the batteries were charging slower and we were potentially losing some of the energy we were trying to store.
Lesson Learned: The slower charging rates and potential energy loss made us realise the importance of having precise control over how quickly our batteries charge. When we can control the charging rates more accurately, we can make sure that we're not wasting any energy and that our batteries are charging as efficiently as possible.
How we solved the challenge: We refined charging mechanisms for precise control over charging rates, minimising energy loss and improving overall energy storage and utilisation efficiency.

Inverter Circuit Implementation:

Challenge: In our initial design (alpha release), our system could only produce DC (direct current) output. This limited the types of devices and applications our system could power, as many devices require AC (alternating current) power to function.
Lesson Learned: The absence of an inverter transformer circuit in our initial design limited the versatility and applicability of our system. We realised that to make our system more useful and compatible with a wider range of devices, we needed to be able to produce AC output as well.
How we solved the challenge: To address this limitation, we decided to implement an inverter transformer circuit in our system. This circuit allows us to convert the DC output from our system into AC power, providing a consistent 220V AC output that's suitable for a wide range of applications.

Monitoring and Control Capabilities:

Challenge: In our initial design (alpha release), the monitoring and control capabilities of our system were basic and rudimentary. We lacked real-time feedback on important parameters such as voltage levels, and we didn't have comprehensive data logging capabilities.
Lesson Learned: The limitations of our monitoring and control capabilities in the alpha release made it challenging to effectively manage and optimise our system. Without real-time feedback and comprehensive data logging, we couldn't monitor the performance of our system closely or identify potential issues in a timely manner.
How we solved the challenge: To address this challenge, we decided to enhance our monitoring and control capabilities by integrating Arduino UNO and LED screen into our system. Through this we can see the real time voltage and footsteps on the screen.

Scope Deviation:

Initially, our project was scoped to address a specific use case, such as powering small electronic devices using piezoelectric energy harvesting. However, as we progressed with our research and development, we discovered additional potential applications for our system beyond our initial scope. We realised that our energy harvesting solution could be adapted for a broader range of uses, including powering remote in environmental monitoring, providing energy for wearable health devices, and even supporting off-grid electricity generation in rural areas.

Impact of Scope Deviation on Schedule:

When the project scope changed beyond the initial plan, it often leads to adjustments in project milestones and deadlines. This is because the additional work required to accommodate the broader scope may take more time than originally anticipated. In our case, when we discovered new potential applications for our energy harvesting system beyond the initial use case, it required us to allocate more time for research and development to ensure that we could effectively address the expanded scope.

- **Reassessment of Timelines:** We first conducted a thorough reassessment of our project timelines in light of the scope deviation.
- **Resource Allocation:** We then carefully reallocated resources, such as team members' time and expertise, to prioritise the tasks associated with the changed scope.
- **Regular Monitoring and Adjustments:** Throughout the project, we implemented a system of regular monitoring and adjustments to track progress against the revised schedule.
- **Flexibility and Adaptability:** Finally, we maintained a flexible and adaptable mindset, recognizing that schedule deviations are often unavoidable in complex projects.

Failure Report

Throughout the project lifecycle, several challenges and setbacks were encountered, leading to valuable lessons learned. While no significant project failures occurred, there were instances where the system encountered issues or setbacks that required attention and resolution. By addressing these challenges head-on, the project team gained valuable experience and expertise, enhancing their problem-solving skills and resilience in the face of adversity. Additionally, the process of overcoming these setbacks fostered a culture of continuous improvement and innovation within the team.

Furthermore, the project's success in navigating these challenges showcased the importance of effective project management practices, including proactive risk management, clear communication, and adaptive planning. These practices helped ensure that the project remained on track and ultimately achieved its objectives.

1st release :

The initial simulation release faced challenges related to voltage generation and rectification. Despite efforts to mimic transducers behaviour accurately, the simulated output did not align perfectly with real-world conditions. Additionally, the reliance on a full bridge rectifier and standard smoothing capacitors resulted in inefficiencies and voltage drops, limiting the system's overall energy conversion capabilities.

Challenges:

Voltage Generation and Rectification: The primary challenge in the initial simulation release was related to voltage generation and rectification. Despite efforts to simulate transducers behaviour accurately, the generated output did not fully replicate real-world conditions. This discrepancy posed a significant hurdle in accurately assessing the system's performance and energy conversion capabilities.

Inefficiencies in Rectification: Another challenge arose from the reliance on a full bridge rectifier and standard smoothing capacitors. While these components are commonly used for rectification purposes, their inefficiencies led to voltage drops and energy losses within the system. These losses diminished the overall energy conversion efficiency and limited the system's ability to harness and store energy effectively.

Lessons Learned:

Realism in Simulation: The discrepancies observed between simulated and real-world transducers behaviour underscored the importance of realism in simulation models. Accurately modelling component characteristics and environmental conditions is crucial for obtaining reliable simulation results that reflect actual system performance. This lesson highlighted the need for comprehensive testing and validation procedures to ensure simulation accuracy and reliability.

Efficient Energy Conversion: The inefficiencies identified in the rectification process highlighted the importance of efficient energy conversion techniques. To minimise energy loss and maximise conversion efficiency, it is essential to use high-efficiency rectifiers and optimise capacitor configurations. By selecting appropriate components and optimising circuit design, it is possible to improve energy conversion efficiency and enhance overall system performance.

2nd release:

The second release encountered challenges related to transducers performance and energy conversion efficiency. The original design, utilising film vibration-based MEMS , failed to generate sufficient power due to transducers limitations and inefficient rectification methods. Despite attempts to mitigate these issues through adjustments to capacitor values and transducers layout, the overall system performance remained suboptimal.

Challenges:

transducers Performance: One of the primary challenges encountered in the second release was related to transducers performance. The original design, which relied on film vibration-based MEMS , struggled to generate sufficient power due to inherent limitations in transducers sensitivity and responsiveness to mechanical vibrations. Despite efforts to optimise transducers layout and adjust capacitor values, the system failed to achieve the desired power output, hampering overall performance and efficiency.

Energy Conversion Efficiency: Another significant challenge stemmed from inefficiencies in the energy conversion process. The rectification methods employed in the second release were unable to effectively convert mechanical vibrations into usable electrical energy, resulting in suboptimal power generation efficiency. These inefficiencies contributed to energy loss and diminished the system's ability to harness and store energy effectively, limiting its overall performance and reliability.

Lessons Learned:

Selecting Appropriate : The failure to achieve desired power output underscored the importance of selecting those that are well-suited to the project's requirements. It highlighted the need for high sensitivity to mechanical vibrations and compatibility with the overall system design. By carefully evaluating transducers characteristics and performance metrics, future iterations of the system can avoid similar issues and achieve improved performance.

Efficiency in Energy Conversion: The limitations of the rectification process emphasised the critical role of efficient energy conversion techniques in maximising power generation efficiency. It highlighted the need for customised rectifiers and advanced energy conversion methods to optimise energy harvesting capabilities and minimise energy loss. By implementing more efficient rectification techniques and optimising energy conversion processes, future iterations of the system can enhance overall performance and reliability.

Final release:

The latest release represents a culmination of iterative improvements and lessons learned from previous iterations. By integrating advanced voltage optimization techniques, customised rectification methods, and comprehensive monitoring capabilities, the current system offers enhanced performance and reliability compared to earlier versions.

Addressing the transducers performance challenge:
In response to the limitations of film vibration-based MEMS in the second release, the latest release of the system adopted a different approach to transducers selection and layout. Rather than relying solely on MEMS , the latest release utilises piezoelectric for energy generation. Piezoelectricity offers higher sensitivity to mechanical vibrations and greater responsiveness, allowing for more efficient energy harvesting. By selecting those that are better suited to the project's requirements and optimising their placement within the system, the latest release overcomes the challenges associated with transducers performance encountered in previous iterations.

Iterative Improvement: The iterative development process allowed for continuous refinement of the system's design and functionality, emphasising the importance of learning from past failures and incorporating lessons into future iterations.

Comprehensive Testing: Thorough testing and validation of each component and subsystem were essential in identifying and addressing potential issues early in the development process, highlighting the value of systematic testing procedures and quality assurance measures.

Lessons learned

1. **Project Planning**: Looking back, the team recognizes the importance of thorough project planning to anticipate challenges and mitigate risks effectively. In future projects, we would allocate more time and resources to the planning phase, ensuring clear objectives, well-defined deliverables, and realistic timelines. Additionally, conducting comprehensive risk assessments and contingency planning from the outset would help mitigate potential disruptions and uncertainties. For example, while working this project we encountered delays during the development phase due to unforeseen technical challenges. With hindsight, we realise that a more thorough risk assessment during the planning phase could have helped us anticipate these challenges and develop contingency plans to mitigate their impact.
2. **Resource Management**: Reflecting on resource management, the team acknowledges the need for better allocation and utilisation of resources throughout the project lifecycle. In future projects, we would implement robust tracking and monitoring mechanisms to ensure optimal resource allocation, budget management, and schedule adherence. This includes regular reviews and evaluations to identify resource gaps or inefficiencies and take corrective actions promptly.
3. **Communication and Collaboration**: Effective communication and collaboration emerged as key factors in project success. Looking ahead, we would prioritise open communication channels, frequent team meetings, and cross-functional collaboration to facilitate knowledge sharing, problem-solving, and decision-making. This includes establishing clear roles and responsibilities, fostering a culture of transparency and accountability, and leveraging diverse perspectives to drive innovation and creativity. For example: During the project execution phase, we experienced miscommunication between team members working on different aspects of the system design. This led to delays in decision-making and coordination issues. In the future, we aim to establish clearer communication channels and promote cross-functional collaboration through regular team meetings and shared project management tools.
4. **Continuous Improvement**: After completing the project, we conducted a post-mortem review and identified areas where our processes could be streamlined and improved. For example, we realised that certain tasks could have been automated to save time and resources. As a result, we plan to invest in automation tools and techniques in future projects to increase efficiency and productivity.

In conclusion, our project journey has been marked by valuable insights, challenges, and opportunities for growth. Through meticulous planning, effective resource management, enhanced communication, and a commitment to continuous improvement, we have navigated through project complexities and emerged stronger and wiser. As we reflect on our experiences and lessons learned, we are poised to apply these insights to future endeavours, striving for greater success, innovation, and impact. With a dedicated focus on planning, collaboration, and adaptation, we are confident in our ability to overcome obstacles, deliver value to stakeholders, and contribute to the advancement of technology and sustainable solutions. Together, we embrace the journey ahead with optimism, determination, and a shared vision of excellence.

Appendix

Meeting Notes

Meeting 1:
Our first meeting was crucial for kickstarting our capstone project coming into the new year for the development of our project. Here's a breakdown of what we accomplished:
Bill of Materials (BoM): We began by creating a detailed list of all the materials needed for our project. This involved discussing what components we already had and what additional items we required to move forward.
Roles and Responsibilities: To ensure everyone's on the same page, we divided up tasks among team members for the upcoming months. Each person was assigned specific responsibilities to keep things organised and efficient.
Procurement Plan: We talked about how to get the materials we needed. Instead of jargon, we decided to buy parts from online stores like Amazon and Digi-Key for their convenience and reliability.
By covering these points in our first meeting, we laid a strong foundation for the rest of our project, setting ourselves up for success as we move forward.

Meeting 2:
We focused on practical arrangements to facilitate the next phase of our project. Here's a concise summary:
1. Logistics Planning: The primary agenda was to finalise logistics for exchanging the parts we ordered. We agreed upon a scheduled time and place for the meetup to ensure a smooth transfer of materials among team members.
2. Circuit Development: With the parts in hand, our next step was to begin constructing the circuit. This circuit would be initially tested on LTspice, a simulation software, to assess its functionality and identify any potential issues before proceeding with physical assembly.
By coordinating logistics effectively and setting a plan in motion for circuit development, we aimed to progress seamlessly into the practical implementation phase of our project.

Meeting 3:
Our focus shifted towards preparing for the upcoming presentation, which involved a peer review of our alpha release. Here's a breakdown of our discussions and assignments:
1. Presentation Preparation: The primary agenda of the meeting revolved around strategizing for the peer review presentation. Recognizing the importance of a cohesive and well-organized presentation, we discussed the key areas to cover and divided roles accordingly.
2. Role Allocation: To ensure a comprehensive coverage of all aspects, we delegated specific responsibilities to team members based on their areas of expertise and interests:Sakhsham and Jeet took charge of the technical aspects, ensuring a thorough examination of our product's functionality and performance. Ahmed was tasked with analyzing the test planning and criteria for the alpha release, ensuring that our testing procedures were robust and aligned with project goals. Navraj conducted a comparative analysis between our product and competitors' offerings, identifying our unique selling points and areas for improvement. Prabhkirat addressed the anticipated challenges that we might

encounter during the alpha release phase, devising mitigation strategies and contingency plans.Gaurav and Rajat focused on highlighting the standout features of our product and outlining the roadmap leading to the beta release, emphasising key milestones and timelines.

By leveraging the diverse skill sets and expertise within our team, we aimed to deliver a comprehensive and compelling presentation that showcases the progress of our project and sets the stage for the next phase of development.

Meeting 4:
We addressed several key points to enhance the efficiency and effectiveness of our project:

Procurement Strategy Refinement: Recognizing the importance of a reliable supply chain, we reviewed our procurement strategy in response to unforeseen disruptions. By identifying alternative sources for essential components, we mitigated potential delays and ensured continuity in our project timeline.
Component Replacement Decision: In light of supply chain challenges and with the aim of optimizing performance, we made the decision to replace our piezo sensors. This adjustment was intended to address any limitations with the existing sensors while aligning with our project objectives of reliability and efficiency.

Meeting 5:
We encountered challenges related to our supply chain, necessitating adjustments to our procurement strategy. Here's a brief summary:
Supply Chain Issues: We discussed unforeseen supply chain disruptions that affected the availability of certain parts essential for our project. To mitigate delays, we swiftly pivoted to identifying alternative sources for these components, ensuring continuity in our progress despite the setbacks.
Piezo Sensor Replacement: In light of the supply chain challenges and to potentially improve performance, we made the decision to switch out our piezo sensors. This adjustment aimed to address any limitations with the existing sensors while aligning with our project objectives.
By proactively addressing supply chain issues and making necessary adjustments to our component selection, we demonstrated adaptability and resilience in overcoming obstacles, thus ensuring the continued advancement of our project.

Meeting 6: Progress Report
During our sixth meeting, our team tackled two critical aspects of our project: conducting a CAD study on the housing unit's deformation and evaluating the output of our circuit design to ensure it could adequately power the cameras. Here's a summary of our discussions:
CAD Study Initiation: We commenced a thorough CAD study to analyse the deformation characteristics of the housing unit under various load cases. This study is essential for understanding how the unit responds to different loads, guiding design refinements and optimizations. While our study began with stainless steel, we acknowledged the importance of considering alternative materials in subsequent analyses to assess their impact on deformation behaviour.
Circuit Output Evaluation: In parallel, we examined the output of our circuit to determine if it could supply sufficient current to power the security cameras. Through detailed analysis and

simulation, we assessed the circuit's ability to generate and sustain the required current levels. This evaluation aimed to identify any limitations in the circuit design and ensure it could reliably meet the power demands of the cameras.
By addressing both the structural integrity of the housing unit and the power supply capabilities of our circuit, we advanced towards our project goals, aiming to optimise performance and functionality while ensuring reliability and efficiency.

Meeting 7: Progress Report and Next Steps
During our seventh meeting, our team focused on organising tasks for the progress report and planning the next steps as the semester draws to a close. Here's a summary of our discussions:
1. Progress Report Preparation: We allocated responsibilities for compiling the progress report, ensuring that each team member contributes relevant insights and updates from their respective areas of expertise. Tasks included summarising achievements, challenges faced, and lessons learned throughout the project's development.
2. Next Steps Planning: With the semester coming to an end, we deliberated on the immediate next steps to keep the project momentum going. This involved identifying critical tasks that need to be completed before the semester concludes and outlining a timeline for their execution.
3. Division of Parts: Additionally, we discussed dividing up any remaining tasks or components to ensure efficient progress in the project's final stages. By assigning specific responsibilities to team members, we aimed to streamline the completion of outstanding deliverables and optimise our use of resources.
As we approach the end of the semester, our focus remains on effectively documenting our progress, planning for the project's continuity, and ensuring that all necessary tasks are completed in a timely manner. This meeting served as a pivotal moment for organising our efforts and setting clear objectives for the weeks ahead.

Meeting 8
As we delved into the final stages of our project, our eighth meeting focused on refining our final report and preparing for the project's culmination:
Final Report Preparation: We began the process of compiling our final report, incorporating insights, findings, and outcomes from the entire project lifecycle. Each team member contributed to summarizing achievements, challenges faced, and lessons learned, ensuring a comprehensive and reflective document.
Final Release Adjustments: Minor adjustments were made to the final release of our project based on insights gained throughout the development process. These adjustments aimed to enhance the overall performance, reliability, and user experience of the system, ensuring its readiness for deployment.

By iteratively refining our approach and leveraging lessons learned from previous meetings, we strengthened our project's foundations and positioned ourselves for a successful conclusion.

Meeting 9:
We had the opportunity to showcase our final product to our project supervisor, providing a comprehensive overview of our achievements and the culmination of our efforts:

Product Presentation: We delivered a detailed presentation outlining the key features, functionalities, and design aspects of our final product. This included a demonstration of the system's capabilities, highlighting its performance and usability in real-world scenarios.

Demonstration of Functionality: During the showcase, we conducted live demonstrations to illustrate how our product addressed the identified problem statement and met the project objectives. This allowed our project supervisor to witness firsthand the effectiveness and reliability of our solution.

Feedback and Evaluation: Following the presentation and demonstration, we welcomed feedback and input from our project supervisor. Their insights provided valuable perspectives on areas of strength and potential areas for improvement, informing our future development efforts and iterative enhancements.

Reflection and Closure: The final product showcase served as a moment of reflection on our journey throughout the project lifecycle. We celebrated our accomplishments, acknowledged the challenges overcome, and expressed gratitude for the support and guidance received from our project supervisor.