IoT Enabled Piezoelectric Energy Harvesting Floormat

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Abstract Energy harvesting through clean energy sources has become a demand nowadays. Internet of Things (IoT) is recommended in an automation system that provides high efficiency and immediate data response. The present study presents a hardware design and software platform used for an IoT enabled piezoelectric energy harvesting floormat. The harvested energy from 16 diaphragm type piezoelectric transducers was stored in a supercapacitor. As for the IoT, the HC-05 Bluetooth module is employed. The prototype has been designed, such that when the user presses the push button, which acts as the switch of the doorbell, a buzzer will sound, and a customized LED lighting pattern will be displayed. With the IoT enabled, the output will be displayed on the PC and cell phone. From the design analysis, the average weight was calculated to be 75 kg while the average Voltage (DC) was 18.5 V and the average current was at 8.5 μA. On a bigger scale, it is projected to be able to generate 42.5 μA per m^2. A typical Built-To-Order (BTO) 4-rooms flat in Singapore which is about 92 m^2, will be able to generate 3.9 mA with 20 steps of a person that weighs 75 kg. Analytical prediction of 29.4 thousand steps required to charge a 250 mAh battery. Considering the average minimum steps produced by an individual is 3.5 thousand steps, it takes around 4.5 to 8.5 days to charge the battery fully.

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Keywords Piezoelectric · Renewable energy · IoT · Green energy

1 Introduction

The world has evolved over 3 revolutions in the past centuries and is in a transition towards the fourth industrial revolution (Industry 4.0) today. Industry 4.0 encourages the use of automation which in turn emphasizes the use of cyber-physical systems. With the involvement of the Internet of Things (IoT), systems can be monitored using digital sensors, and information can be transmitted and received in real-time in addition to storing data over cloud servers and networks [1]. With such accelerated advancements in technology, the use of electricity is inevitable in modern society [2]. Hence, a huge emphasis has been placed on alternate methods of energy harvesting. Energy harvesting through renewable resources refers to harvesting energy that is clean and constantly replenished through natural resources. The most commonly known energy harvesting sources are wind energy, tidal energy, geothermal energy, and solar energy [3]. However, energy harvesting can also be implemented small scale by converting mechanical energy in the surroundings to usable energy [4]. Energy can be harvested from the environment by capturing small-scaled wasted energy and using it to supply power to systems that require low power, ranging from μA – mA [5]. Wasted energy is the energy that has not been fully utilized or lost to the ambient after its primary source. Wasted energy exist in forms such as heat, force, light, and vibrations [6]. One such way of harvesting force as wasted energy is by utilizing human movement activities as the source of input [7]. The average number of steps per day ranges from about 3.5 thousand to 6.9 thousand for an individual across the world [8]. For every step taken, useful energy is dissipated for movement in a desired direction. However, the force applied to enable this movement is gone to waste. Such wasted energy is targeted to be harvested by using a piezoelectric energy harvesting floormat.

Piezoelectric crystals are made of atoms that are positively charged and negatively charged. By compressing the quartz crystals in the transducer, the centre of charge between the positively charged atoms and the negatively charged atoms changes in an opposing direction. As a result, when a force is applied, at the faces of the crystals, it is observed that on one end it is positively charged while the is negatively charged. By wiring both ends, there will be a transfer of electrons thus, electricity is generated [9]. The piezo pavement was installed on an actual walkway and used to power walkway signal indicators. The data collected on the amount of electrical energy is monitored by a mobile application and website information by the means of wireless communication. The maximum output power of this harvester (with a resistance of 10 kΩ) was measured as 148.3 mW, as a person weighing 100 kg walked over the pavement [10]. The idea of piezo pavements had been developed by Pavegen and installed in a few countries such as Hong Kong, London, United Arab Emirates [11]. Pavegen harnesses the power of every footstep to generate instant clean electricity for applications such as ambient lighting or data screens and display monitors. The piezoelectric energy harvester shown by Jeong et al. (2019) are designed to power LED strips that are fitted at the base of the shoes [12]. The shoes consist of a piezoelectric device (PZT ceramic), which is placed at the insoles of the shoes. With every step taken, the force input by the motion of the user is converted into electrical energy. The highest output of the piezoelectric energy harvester is measured to be 800 μW with a resistance of 400 kΩ. It is able to control the LED switching circuit thereby blinking upon the user's movement. The rectified voltage can be connected to the supercapacitor to store energy, or a load can be added at the DC out to power other components for the piezoelectric energy harvesting system [13].

IoT is a digitalized network communication system that enables real-time interactions between humans and machines. This is made possible through wireless communications between networks and sensors [14]. IoT network communication encompasses a wide spectrum of communication platforms. IoT devices include cell phones, routers, smart wearables such as smartwatches, and also Global Positioning System (GPS) that is installed in vehicle navigation systems. The communication technologies involve Bluetooth, LoRa, ZigBee, Wi-Fi, LTE, and 5G network. It can be further developed into applications and network services for various functions that include monitoring and data analysis as well [15].

Bluetooth is widely used for smart home automation purposes. It is highly favourable due to contributing factors such as low power consumption, affordable cost, and compact within devices [16]. A smart switching motor control by Karthick et al. (2021) was introduced in an industrial setting where typically a distance of 500 m is travelled to turn on/off motors [17]. The HC-12 Bluetooth module was utilized to transmit data and thereby enabling control of the ON/OFF functions of motors. This is done by the user providing the input to either ON or OFF the motor. This information is transmitted to the receiver over a 500 m range during which the LED will illuminate. The PIC microcontroller will then regulate the motor according to the user's input. A home automated control system with IoT using Bluetooth had been designed by Amoran et al. (2021) [18]. The HC-06 Bluetooth module was programmed with an Arduino microcontroller to enable the user to control the ON/OFF functions of home-based electrical appliances. It supports the Google assistant voice-prompt feature that is incorporated within the android operating system thereby functions well with smartphones too. It has an additional 12-h timer function which can be set by the user via smartphone. The working principle is such that the user connects to the Bluetooth module and sets the preferred setting which will be transmitted to the appliances that are connected to the Bluetooth. The appliances then receive the data and execute the command accordingly.

In this study, it is identified that the prototype for energy harvesting can be done by using piezoelectric transducers with PZT ceramics such as the diaphragm type or cantilever type. The circuitry for energy harvesting can be done by connecting an array of piezoelectric transducers input to the bridge rectifier and the output can be stored in a supercapacitor. IoT can be incorporated via Bluetooth module. Human movement can be perceived in various forms such as walking, jogging, jumping, or many more. However, the main focus in this study is human movement through footsteps-related activities, specifically walking on a floormat.

2 Methodology

The methodology flowchart for the present study shown in Fig. 1. The present study begins with the identification of the required list of components from the literature study, followed by the design brainstorming and design selection. Then the hardware and software design for an IoT enabled piezoelectric energy harvesting floormat will be discussed.

2.1 List of Components

In this study, there are several components have been to build the prototype and display the harvesting energy. All the components have been set accordingly to collect the proper and accurate data. These components are functioning by sending the signal to the PC or the phone to indicate the number of the footsteps, temperature, as well as the buzzer sound to notify the owner of the unit if there is any visitor has been pressed the doorbell. All these components have set by LPC 1768 microcontroller. The list of components used for the prototype is listed in Table 1.

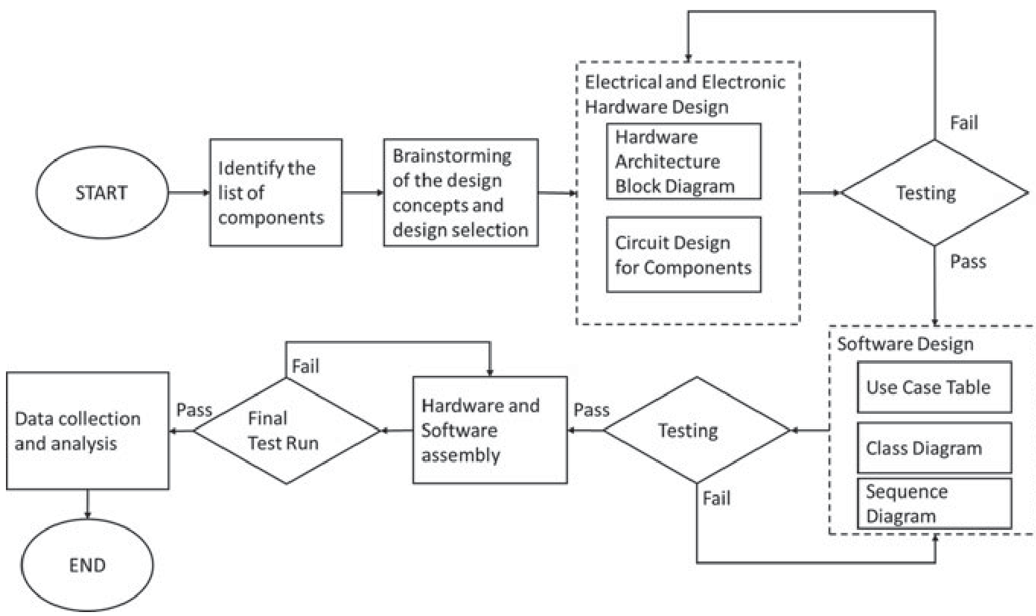


Fig. 1 Methodology flowchart

Table 1 List of components

Component	Function
LPC 1768	Microcontroller (MCU) used to support the monitoring system and execute command for the output functions
Piezoelectric Transducers	To harvest energy from user 1 footsteps
Buzzer	For audio alert to notify the owner (user 2) that a visitor (user 1) has pressed the doorbell
Temperature Sensor	This is an additional feature that measures surrounding temperature and provides data to user 2
Push Button	For the start-up of the device and the doorbell switch function
Bluetooth module	Sends the data to user 2 mobile phone and PC

2.2 Selected Design Concept

The selected design concept is the piezoelectric energy harvesting floormat. The floormat concept allows a low cost and small-scale prototype to be developed. For better visualization of the expected outcome of the design concept, a "SketchUp" model was done. SketchUp is a 3D design software that allows users to perform 3D modelling online [26]. It has templates that are ready for use and can be put together to bring ideas to a realistic modelling concept as shown in Fig. 2. A prototype, 20 by 20 cm, was built based on the finalized idea as shown in Fig. 3.

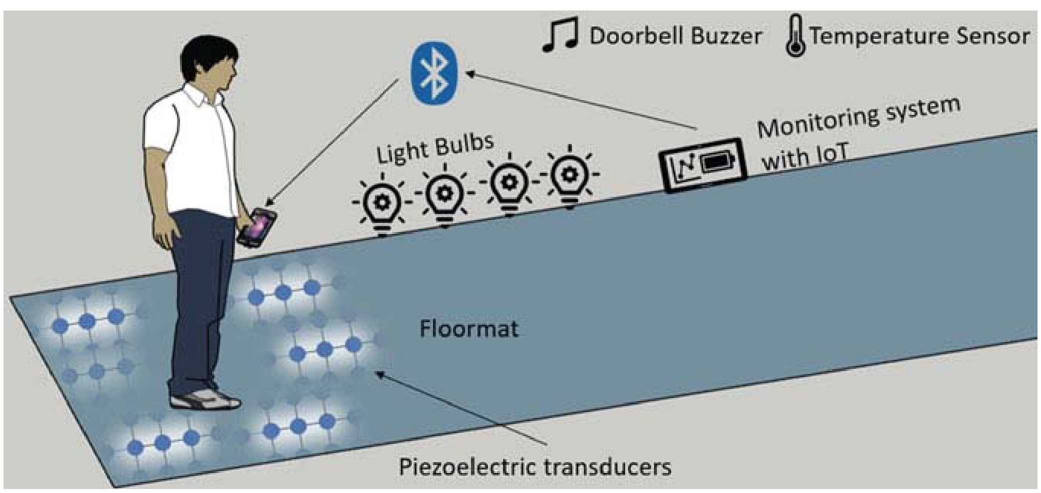


Fig. 2 Design visualization

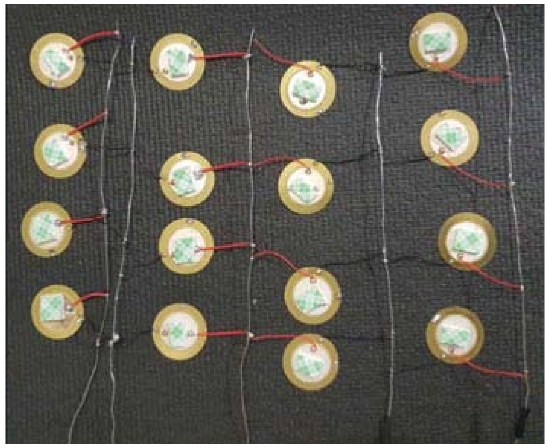


Fig. 3 Prototype of piezoelectric floormat

2.3 Electrical and Electronic Hardware Design

Hardware Architecture Block Diagram

The hardware architecture block diagram maps the connections between the electronic components and the MCU as shown in Fig. 4.

Circuit Design for Components

The National Instruments MultiSim 14.2 software was used to design the complete circuitry of the prototype. In the energy harvesting circuit, the voltage generated from the piezoelectric transducer is in AC. Therefore, it needs to go through a bridge rectifier to convert the AC voltage to a DC voltage. 4 diodes are connected in a

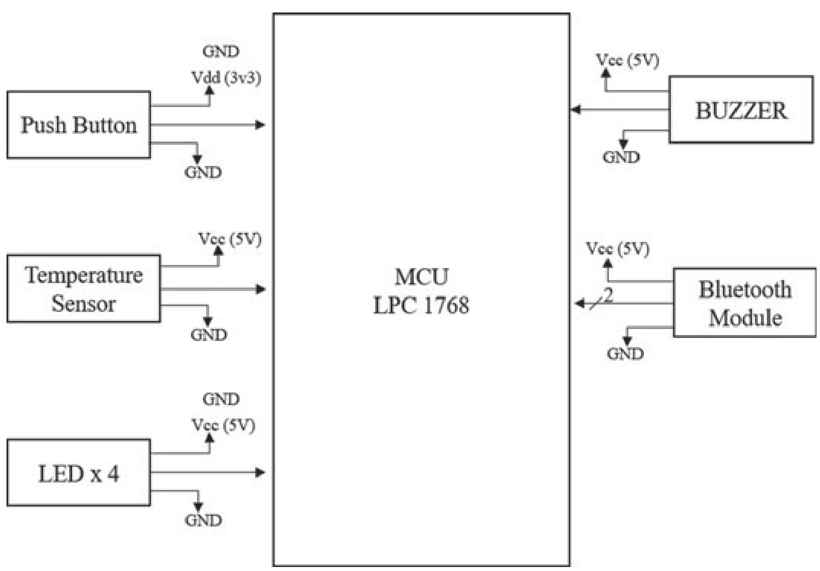


Fig. 4 Electronic hardware architecture block diagram

full wave rectifier configuration. DC voltage across the rectifier output terminals is connected in parallel to the supercapacitor to be charged.

There are 4 LEDs used in this prototype and connected to the MCU board. The HC-05 Bluetooth module communicates via the transmit and receive pins to exchange information with the MCU. The HC-05 module is powered up by 5 V Vcc. Since it is a bi-directional communication, the transmit pin of the HC-05 should be connected to receive pin of the MCU, vice versa. Since the push button is designed to execute an interrupt event in this prototype, it is connected to Pin 13 of the MCU. As the buzzer draws a high current therefore a resistor should be placed before connecting it to the MCU to protect the component.

In this prototype, the LMT 84 is connected directly to the MCU and read as an analog signal. This analog signal is manipulated in the program code and output a voltage within the allowable limit of the MCU. The schematics of the individual components of the prototype were all combined together to form the Project's Schematic Capture as shown in Fig. 5.

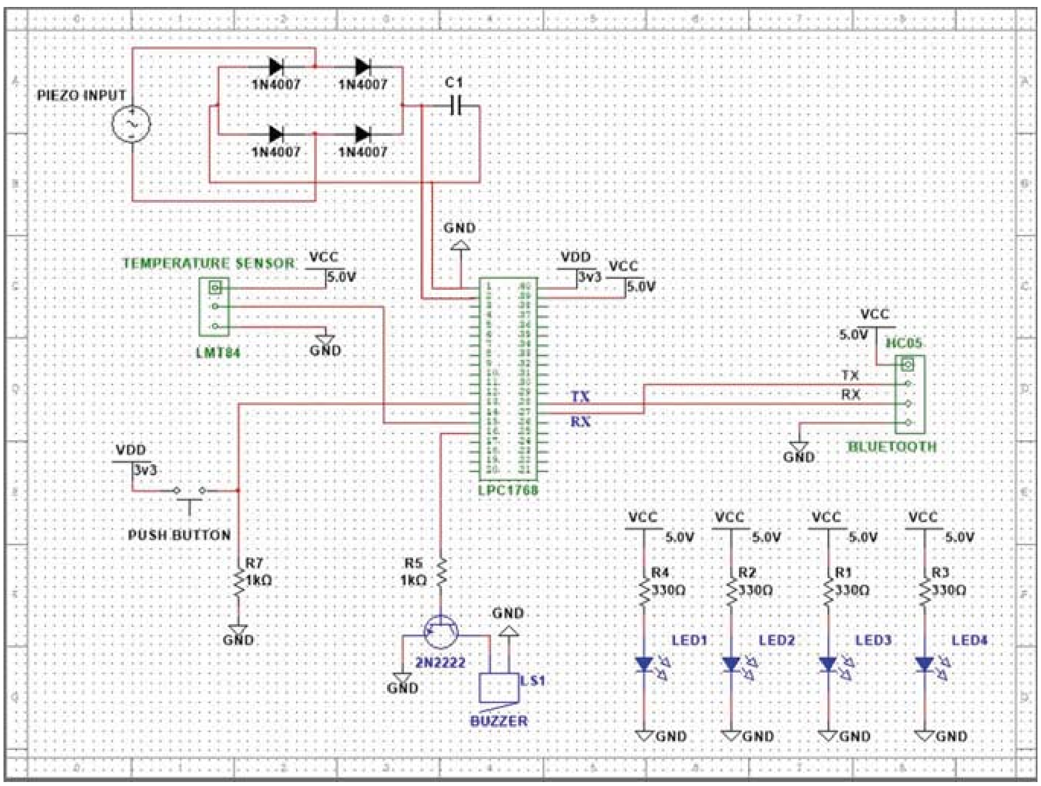


Fig. 5 Project's schematic capture

2.4 Software Design

The software design was modelled by an online program, “Visual Paradigm” while the coding was done by an online compiler, “Mbed Online Compiler”. The “Mbed Online Compiler” can be downloaded or used as an online tool to perform “C” or “C++” coding and build the program. By accessing it online, the software updates and libraries are automatically stored up to date and each program file can be accessed anywhere over the web. Upon completion of coding, it builds a successfully coded program in a “.bin” binary file output. Visual Paradigm is an online tool that is used by professionals to model through the Unified Modelling Language (UML) diagrams. The UML segregates the software into 2 aspects, structural and behavioural. The UML modelling in software development is crucial in Object-Oriented programming, as it can be used to build the program based on its Use Case, Classes, and Sequence of execution, each of which will be presented in the sub sections.

Use Case Table

The Use Case can exist in the form of a table or in the form of a diagram representation. In this study, it will be represented in the form of a table. It consists of information on the system’s response to the Human Action Input as shown in Table 2.

Class Diagram

A Class diagram is a representation of the classes, the “attributes” and the “operations” as shown in Fig. 6. The “attributes” denoted with the “-” in the beginning, indicates the variables that are used in the coding while the “operations”, denoted with “+” in the beginning, indicated the method of the execution.

Table 2 Use case table

Human action	System response
Turn on the device	Initialization of device and components Main Scenario: • MCU initializes the components • Buzzer turns off • Temperature sensor initializes • Bluetooth initializes Optional Features: • Bluetooth displays “Bluetooth Ready”
Visitor detection (visitor press pushbutton)	• MCU sends a signal to initialize Buzzer • MCU transmit information to Bluetooth to notify the Owner • Buzzer sounds for 5 s • LED light display for 5 s (customized pattern)
Temperature detection (additional feature)	• MCU initialize Temperature sensor • Temperature is measured and data is sent to MCU • MCU transmits information to Bluetooth to transmit to the Owner

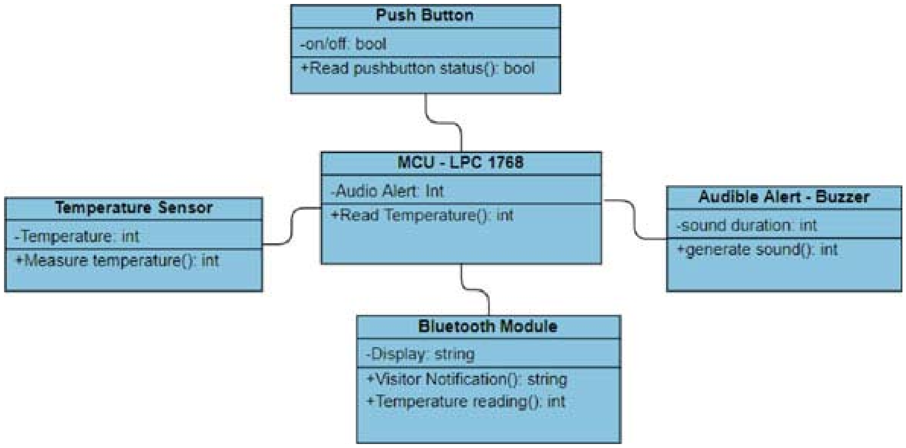


Fig. 6 Class diagram

Sequence Diagram

As shown in Fig. 7, the sequence of events is depicted through the Sequence Diagram. User 1 refers to the Visitor at the doorstep, while User 2 refers to the Owner. As visitors' step on the Energy harvesting floormat, it will store the energy in a rechargeable battery which can power up the MCU. The MCU will then begin to send temperature feedback to User 2. When the push button, doorbell switch, is pressed the Buzzer will give an audible output to both Users. In addition to that, User 2 receives a notification via Bluetooth that there is a visitor while User 1 gets a customized LED output lighting, which could display a "Welcome" sign.

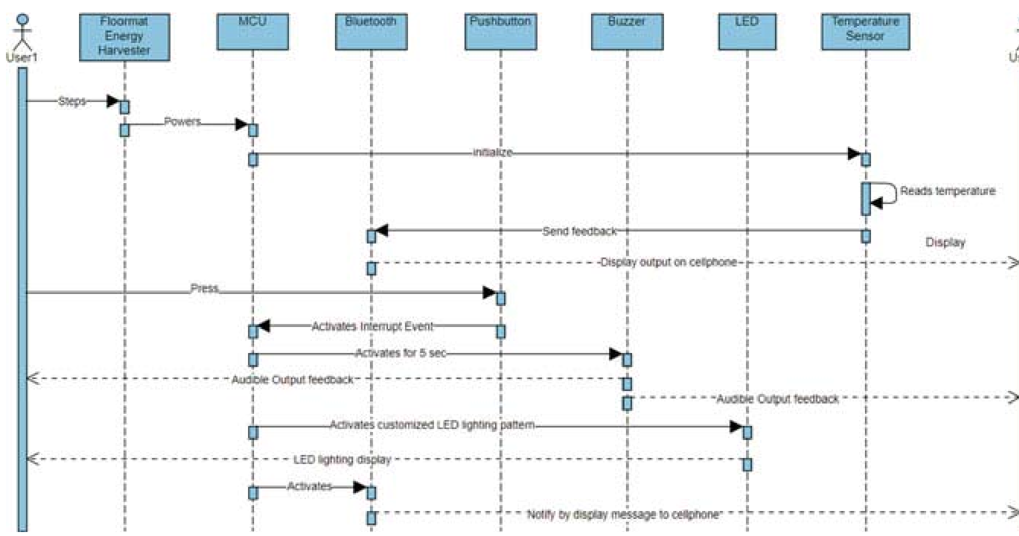


Fig. 7 Sequence diagram

3 Results and Discussion

The hardware and software were integrated, and the evaluation results were recorded. The floormat prototype was stepped on, as shown in Fig. 8. The energy generated was monitored by using the multimeter and the microcontroller as shown in Fig. 9. The prototype has been evaluated and 20 data has been collected from 3 load tests, which each loaded with 44, 77, and 105 kg, respectively (family member weight). The DC voltage and current results are presented in Fig. 10 and Fig. 11 respectively.

As shown in Fig. 10 and Fig. 11, the different weights have an impact on the amount of energy harvested. It is observed that both voltage and current produced varies with the weights. Heavier weights cause higher mechanical pressure on the piezo transducer, generating higher amounts of electrical energy. Taking the average readings, the average weight was calculated to be 75 kg while the average Voltage (DC) was 18.5 V and the average current was at 8.5 µA.

Since a 20 cm-by-20 cm floormat that fits 16 piezoelectric transducers can generate about 8.5 µA, in a bigger scale, it is projected to be able to generate 42.5 µA per m^2. A typical BTO 4-room Flat in Singapore which is about 92 m^2 will be able to generate 3.9 mA with 20 steps of a person that weighs 75 kg.

Fig. 8 Stepping on Piezo floormat

Fig. 9 DC Voltage reading

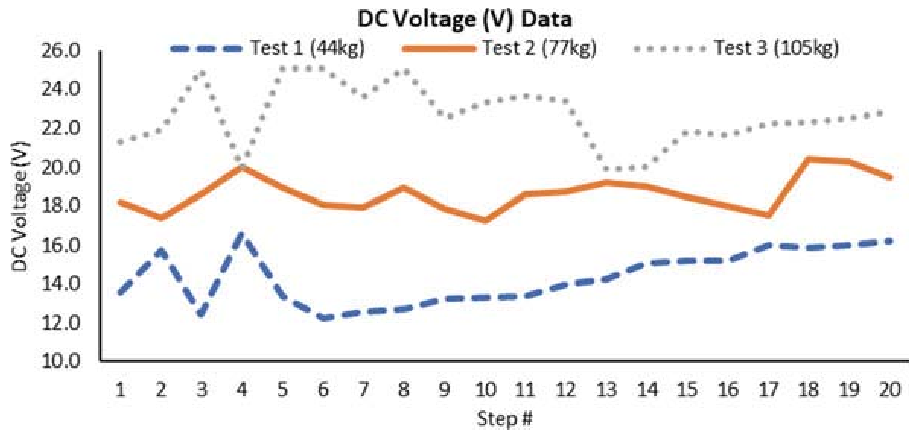


Fig. 10 DC Voltage (V) data

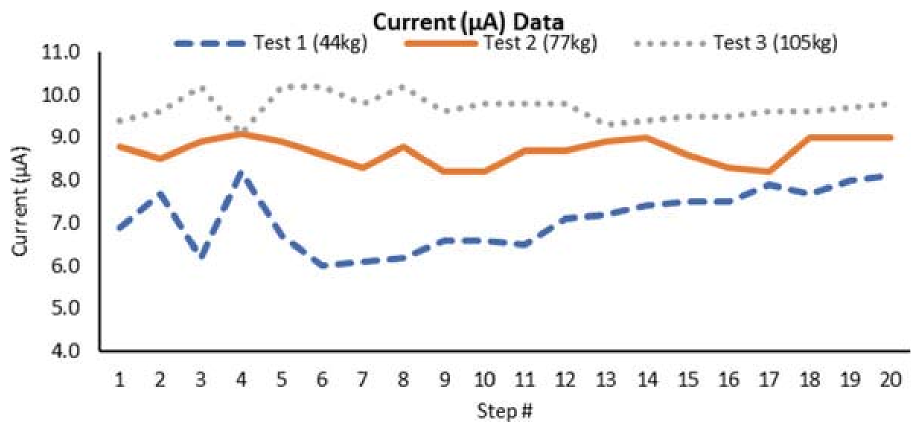


Fig. 11 Current (μA) data

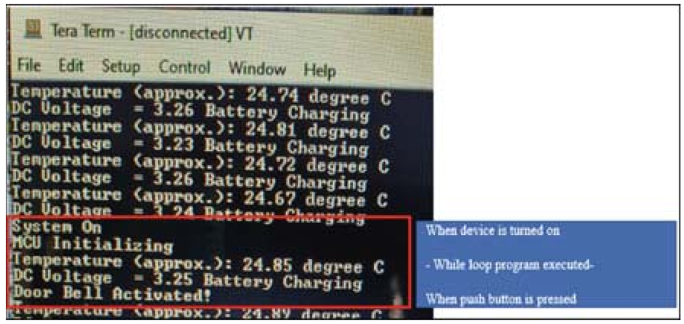
With the average current, a 250 mAh battery will take about 29.4 thousand steps to be charged fully as calculated based on Eq. (1).

$$\begin{aligned} \mathit{Number\ of\ Step\ Required} &= (\mathit{Battery\ Capacity})\big/(\mathit{Average\ Current}) \\ \mathit{Number\ of\ Step\ Required} &= (250\,\mathrm{mA})\big/(8.5\,\mu\mathrm{A}) \approx 29412 \end{aligned} \tag{1}$$

Based on the average number of steps taken for an individual which ranges from 3.5 thousand steps to 6.9 thousand steps [8], it is projected to take approximately 4.5 to 8.5 days to completely charge the battery fully.

The software was tested to see if the system can be triggered, initialized, and display deliverables. When the MCU is turned on, the system was able to read the temperature, charged capacity of the battery and its status. When the push button is pressed, the system was able to detect and notify the user. The expected readings were captured in the Tera Term terminal as shown in Fig. 12.

Fig. 12 Capture of PC output



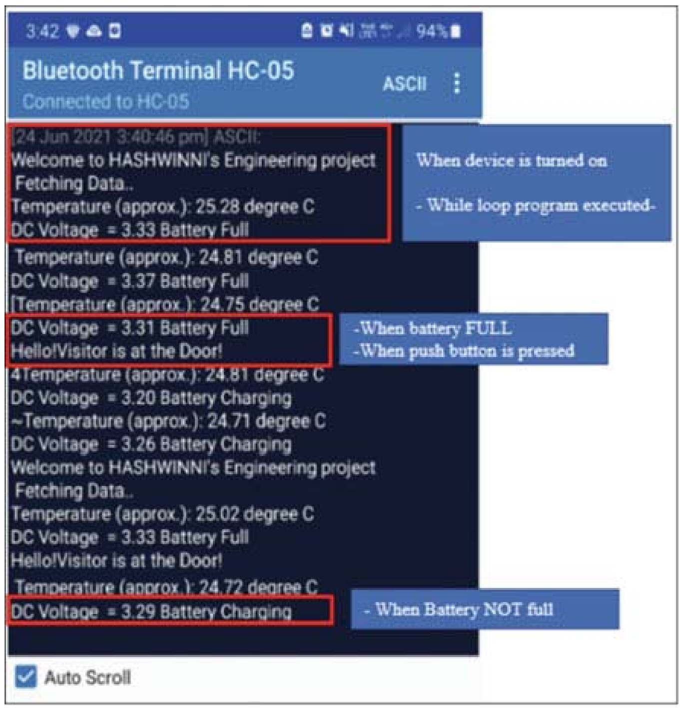


Fig. 13 Capture of cell phone output

The readings were also programmed to be displayed on the cell phone by accessing through a mobile application, "Bluetooth Terminal HC-05", that can be downloaded from *Android Playstore* as shown in Fig. 13 as the capture of cell phone output.

4 Conclusions

In conclusion, this study presented the design of an IoT enabled piezoelectric energy harvesting floormat, the small-scale prototype has been designed and fabricated for evaluation. The prototype consists of diaphragm type piezoelectric transducers powered by the LPC 1768 MCU and the HC-05 Bluetooth module for data transmission. Analytical calculation results based on the data collected from the floormat estimated the average output of 18.5 V (DC) and 8.5 μA with 20 steps of a person that weighs 75 kg. It is also projected with 42.5 μA output per m^2 and 29.4 thousand steps to fully charge a 250 mAh battery which takes approximately 4.5 to 8.5 days.

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