Development of a Portable Human Motion Energy Harvester

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Abstract

This paper addresses the design considerations in constructing an energy harvester from human motion, guided by electromagnetic induction principles. With preliminary experiments conducted, the performances of various prototypes were evaluated in terms of voltage and current output. The fabrication of the final prototype and electronics of an AC to DC power supply unit is discussed. The energy harvester is optimised to charge two 2800mAh Ni-MH rechargeable batteries of 1.2V. For a single battery, the minimum and maximum watt-hour of the energy harvester operating in the linear charging curve range is 1.142±0.129Wh and 1.427±0.161Wh in 20 minute intervals at 2.4V and 3V respectively. It is characterised by charging a battery from 0.18V to 1.08V in 93 minutes by running at 10km/h on a treadmill, translating to a 91.64% increase in the potential difference across the battery. The total minimum and maximum watt-hour generated in 93 minutes is 6.270 and 7.837Wh. Further improvements of the energy harvester include miniaturisation, better ergonomic design for increased comfort over a long period of time and restoring mechanisms to boost output in the slightest vibrations.

1. Introduction

The average iPhone of 1440mAh would require a total of about 2kWh a year, and including that of an iPad and a laptop, that would total to around 100kWh a year. This means an average person who uses the 3 devices would pay around $10 worth of electricity a year [1]. Considering the number of users based on the population in Singapore, the consumption of electricity would definitely be sizable. On the macro scale, governments and many corporations are putting in their efforts to harvest and generate energy from renewable resources. Examples include wind, solar and hydro generated power. While the amount of energy generated by such power plants is massive relative to the amount of electricity used on an individual level [2], the amount of electricity used collectively as a whole population is comparable to that produced by these plants. As such, this leads to the question of whether this energy could also be generated on a personal level. This implies the scaling down of energy harvesting to an individual level, allowing one to generate his or her own power to charge personal devices. Thus, this will reduce the dependency on power supplied by electrical companies and the overall carbon footprint resulting from the by-products of traditional plants.

As the number of electronically powered hand held devices is continually increasing in the market, the need for energy storage devices used as an emergency power supply has also been increasing. Specifically, the ones that are light, portable, affordable and have a large capacity to charge one's personal electronic devices seem to be in high demand. While conventional batteries like lithium-ion batteries and nickel-based batteries serve to provide an energy source, it does not reduce the amount of energy being consumed.

Since the 1930s, there have been various forms of generators that were invented. Electromagnetic power generation is not something new to the field of energy harvesting. It is evident that it is an established technology that has been well researched and developed in. While it does not favorably scale down to a personal level relative to piezoelectric and MEMS technology harvesters that are in the market, its simplicity in concepts, design and flexibility for general use gives it an advantage. It is not limited by the stress that a piezoelectric material can withstand, allowing for a wider range of amplitude of motions [3]. Also, since it relies on the acceleration in motion which directly affects the rate of change in flux of the magnetic field, the design can be based on the frequency of vibrations which accommodates for a huge range of frequencies. Lastly, it does not rely on technologically intensive tools such as those involved in designing a MEMS circuit. Given extensive research and well thought out design considerations, simple magnets and coils can generate a significant amount of electricity to power and charge batteries for everyday use, especially when an emergency electricity supply is needed.

Considering the above, this project aims to harvest energy from electromagnetic induction given the simplicity of design and its suitability towards the application of using human motion as part of their daily activities to generate electricity. Generating electricity using this concept would thus be effortless and unintentional. At the stage of pilot testing, the energy harvester is targeted for use solely in the gym, utilising gym equipments that provide a relatively long workout duration and high intensity movement. These exercises include the running on treadmills and cycling on cycling machines. The energy harvester is be attached to the side of the shoes of the user during the workout, with the harvester parallel to the ground. The displacement of the magnets through the coil will generate an electromotive force, which will be used to power hand held devices that are ubiquitous in today's society.

The desired output of the energy harvester is to be able to charge two 2800mAh Ni-MH rechargeable 1.2V batteries within a day's workout at the gym. The energy harvester is optimised for its portability and efficiency in charging, in terms of higher current output. The dimensions of the energy harvester is based on an average adult's shoe size, allowing comfort without restricting movements. The detailed design considerations and fabrication process is discussed in Section 2 and 3. The performance of the energy harvester is presented and evaluated in Section 6 for its application, optimisation and further improvements.

2. Design Considerations

2.1. Electromagnetic Induction System

The fundamental Faraday's law of induction in Equation 1 is explored when devising an instrument to convert kinetic energy from motion to electrical energy in terms of electromotive force (emf) ε from electromagnetic induction. An electric current that arises from this potential difference can be used to charge a battery for energy storage.

$$\varepsilon = -N\frac{d\Phi_B}{dt} \tag{1}$$

$$\Phi_B = \int_S \mathbf{B} \cdot d\mathbf{A} \tag{2}$$

To maximise the emf for maximum electrical output, a high rate of change in magnetic flux experienced by the coil is vital. This can be achieved by increasing the frequency in which the magnet moves into and out of the coil, having a large number of turns N in a coil and high magnetic flux Φ_B. The energy harvester has to be designed in a way that the fixed coils are positioned as close to the moving magnets as possible, where the highest $\Delta\Phi_B$ occurs. The configuration of having coils on the outside and magnets on the inside (illustrated in Figure 2 in Section 3) is more favourable as magnetic field lines can extend to cut the coils more effectively. Also, energy generation is more effective when the magnets oscillate faster (at higher frequencies) or have abrupt changes in direction. Hence, the material encasing the magnets has to have low friction between both surfaces to ensure smooth sliding.

In addition, according to the Lenz law (Equation 1), the electrical energy generated as the magnets move in and out of the coils, is in the form of an alternating current. This alternating current has to be rectified through electronic circuits (discussed in Section 4) so as to produce a direct current power supply unit, which effectively charges the battery.

2.2. Magnet Properties

As Φ_B is defined as the surface integral of the normal component of the magnetic field $\mathbf{B}$ passing through that surface $\mathbf{A}$ (Equation 2), given a fixed area, Φ_B can be determined by its magnetic flux density or surface Gauss value. As thicker magnets have higher Gauss values, a balance between usability and output in terms of length and higher emf produced has to be reached.

The magnet's material and its grade can also affect the Φ_B. Higher magnet grades of strong rare earth elements have higher magnetic strengths. For example, N50 grade Neodymium magnets can be used to produce a reasonable amount of electrical energy. Despite having a low resistance to corrosion (compared to ceramic and Samarium Cobalt) and a lower break down temperature (compared to alnico and Samarium Cobalt), Neodymium is chosen based on magnetic field strength, coercive force and cost.

The magnetic field lines of different magnet shapes (Figure 1) were also compared such that magnet movement was maximised for the highest electrical ouput. While the magnetic field lines of different shapes of magnets yield little to no difference as all common magnets have a north and south dipole, the behaviour and ease of construction using magnets of different shapes was evaluated. Sphere magnets were unsuitable as it is impossible to keep the poles in place. Ring magnets provides a lower surface area and thus a lower magnetic flux compared to cyclindrical disk magnets. Hence, magnets of two main shapes - cuboid (rectangular and square) and cylindrical disk magnets were constructed and tested in preliminary experiments for comparison of electrical output in Section 5.1.

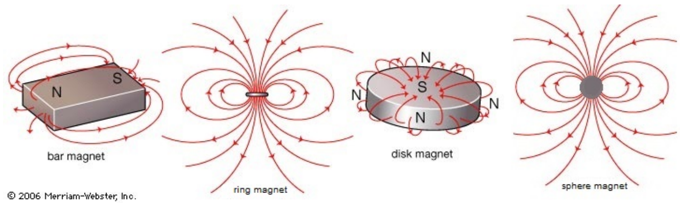

Figure 1: Magnetic field lines of a bar, ring, disk and sphere magnet [4].

2.3. Coil Properties

While it is clear that a higher number of turns is desired to generate a higher emf, the length of the wire L used increases as the number of turns N increases, thereby increasing the resistance R, as seen in Equation 3. Given a fixed coil holder size, the length of the wire L is inversely proportional to the cross sectional area A. A smaller cross sectional area A from a smaller diameter of coil wire results in a longer length of wire L, which in turn produces higher emf output but a lower current output due to a higher resistance. This relationship is illustrated in Equation 4. Thus, the diameter the coil wire has to be optimised between the voltage output for charging two batteries and current output for faster charging.

$$R = \frac{\rho L}{A} \tag{3}$$

$$V = IR \tag{4}$$

3. Prototypes

As the energy harvester is to be used with effortless and unintentional human motion, the energy harvester has to be relatively small and light weight, allowing comfort without restricting movements. Taking into account the separation distance of two magnets in repulsion, a basic prototype accomodating 4 magnets is conceived in Figure 2 for maximum magnet displacement within the length of an average adult's shoe size. Four magnets arranged in alternating poles in repulsion with each other are placed in a tube to oscillate freely with motion. Three coil holders are fixed around the tube and are positioned close to the magnets at equilibrium such that the change in magnetic flux is maximised.

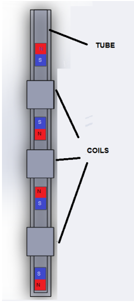

Figure 2: Outline of basic prototype, consisting of 3 fixed coils and 4 moving magnets arranged in alternating poles to repel each other.

3.1. Shape and Material of Prototype

Rectangular and cylindrical prototypes based on the basic prototype outline were constructed with different materials - thin plastic sheets and acrylic (Figure 3). Initially, thin plastic sheets of less than 1mm (Prototype (a) and (b)) were used for the prototype as coils could be placed closer to the magnets for a maximum change in magnetic flux. However, the plastic sheets proved to be too flimsy to conduct proper experiments to accurately capture its electricity output. Prototypes (a) and (c) were fabricated by bending and folding a piece of plastic sheet by hand. Kinks in the tube due to difficulty in constructing a perfect tube, created friction between the magnets and the plastic sheets, and thus leading to a lower electrical output than expected. As such, this led to the fabrication of prototypes with a more rigid and sturdy material, acrylic, despite having a minimum width of 2mm.

Prototype (d) was fabricated by attaching laser cut acrylic pieces together while prototype (c) was made of a manufactured acrylic tube. The dimensions are specifically calculated to prevent the flipping of the magnetic poles, yet ensuring a gap between the tube and magnets for an almost frictionless movement. Prototype (c) consists of 4 sets of 4 magnets attached together, represented as one magnet in Figure 4, to prevent the flipping of the magnets. This also increases the magnetic strength in the process. In designing a flat and sleek energy harvester, prototype (d) consists of rectangular magnets with stronger magnetic flux on the sides with a smaller cross section. Both prototypes had 3 coils of 700-900 turns.

Preliminary experiments (refer to Section 5.1) were conducted to investigate the voltage and current input of prototype (c) and (d). The resulting electrical outputs of both prototypes at 12cm amplitude and a range of frequencies of 1 to 4Hz are compared in Figure 5. The prototypes produced a voltage output ranging from 2V to 6.3V and current output ranging from 10 mA to 50 mA. The maximum current and voltage of 53mA and 6.3V respectively were obtained with prototype (c) at 4Hz and 15cm. As expected, an increase of both voltage and current was also observed with a higher amplitude and frequency for both prototypes. While it is highly likely that prototype (c) generated a higher electrical output due to its high surface area and thus that the effect shape of the magnet is inconclusive, it was observed from the preliminary experiment that the circular disk magnet allowed smoother displacements. The rectangular magnets, on the other hand, were often caught stuck at its edges causing the magnets to stop abruptly in motion. Prototype (d) had to be nudged a few times before returning to its original position. Hence, the cylindrical body with disk magnets was chosen as the base shape of the prototype.

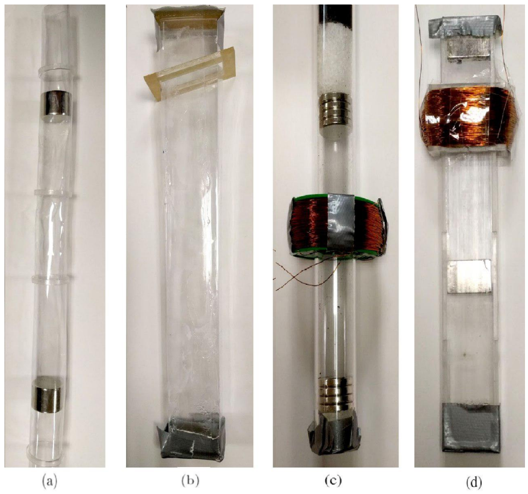

Figure 3: Thin plastic prototypes using (a) cylindrical magnets and (b) rectangular magnets and Acrylic prototypes using (c) cylindrical magnets and (d) rectangular magnets.

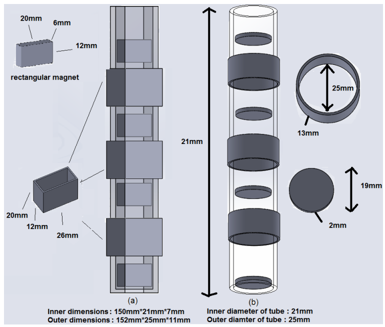

Figure 4: Detailed dimensions of Acrylic (a) Rectangular prototype and (b) Cylindrical prototype.

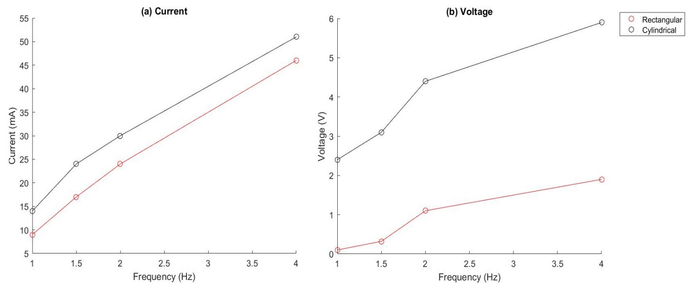

Figure 5: Current and Voltage output of the rectangular and cylindrical prototype at an amplitude of 12cm, with varied frequency.

3.2. Coil wire diameter of Prototype

By conducting a similar experiment described in Section 5.1, the electrical output of thin and thick wires used for the coils are compared in Table 2. To charge two 1.2V batteries, the emf generated would have to be maintained above 2.4V, after taking into account the voltage drop from the electronics. While voltage is crucial in the determining the number of batteries that can be charged, current determines the amount of time needed for the battery to be fully charged.

Copper wire thickness	0.2mm	0.5mm
Number of turns	1500-1800	500-600
Voltage Output	6.6V	4.0V
Current Ouput	38mA	60mA

Table 1: Current and Voltages generated from coils made of wires with different thickness

Since the output voltages of both coils are well above the minumum voltage required, the wire of diameter with the higher output current was chosen to decrease the time taken to charge the battery with the same amount of charge. Using the thicker wire, in theory, reduces the amount of time needed to charge the batteries by 50% relative to the thinner wire, hence improving the efficiency of the energy harvester.

3.3. Final Prototype

To boost the electrical output in minimal vibrations, springs placed at the top and bottom of the tube were initially considered to provide a restoring force for the magnets. However, due to the attraction of the springs to the sides of the magnet with higher magnetic flux, it was difficult to secure the springs in the desired position. An array of springs was also considered however it was unable to the load of movement and thus it came apart during the testing.

Figure 6: Final Prototype used in the gym to charge a 1.2V battery by running on the treadmill.

Sponges were placed at the top and bottom of the tube to reduce the impact of the magnet crashing into the lid of the tube, so as to retain as much of the magnetic field strength as possible. Straps were also added to the final prototype (Figure 6 for a hands-free convenience.

4. Electronics

Due to the nature of the energy harvester's application, the alternative voltage generated is irregular and of low frequencies ranging from 1.3 to 4Hz. To provide a direct current power supply maintained above 2.4V to charge two 2800mAh Ni-MH rechargeable batteries of 1.2V, the induction coils is to be coupled with a rectifying circuit with smoothing capacitors.

In designing the electronic circuit for the energy harvester, a full wave bridge rectifier is best suited for this application, despite a 1.4V drop across the rectifier. It maximises the voltage and current output, especially in compensating the inefficiencies resulting from low frequency discontinuous human motion. Based on preliminary experimental values, an average amplitude of 5V is generated from the energy harvester. This leaves an ample amount of potential across the load to charge two 1.2V batteries even with the 1.4V drop.

Given the preliminary results from Section 5.1, the voltage ranges from 2V to 6V and current I_{load} ranges from is 10mA to 50mA. To over engineer the system to accommodate the smallest possible energy output, the given parameters of I_{load} = 10mA, V_{pp} = 0.72V (20% peak to peak ripple of 3.6V) , f = 1.3 Hz are used in Equation 5 to calculate the ideal capacitance value for a full rectified wave.

$$V_{pp} = \frac{I_{load}}{fC} \tag{5}$$

With a calculated capacitor value of 5341 μF, the optimal capacitor value is further investigated using simulated values with LTspice[5]. The simulation uses a 5V AC sine wave source and a load of resistance 10Ω. The capacitance values are varied from 100μF to 13200μF at a frequency of 2 Hz, as shown in Figure 7. The root mean square voltage across frequencies from 1.4 to 4Hz is also compared in Figure 8. At 13200 μF and the lowest frequency of 1.4Hz, the minimum voltage output slightly above the battery voltage obtained is 2.4239V. A capacitance higher than 13200 μF would certainly increase the root mean squared voltage and thus increase the efficiency of the energy harvester. However, to optimise the voltage output (above 2.4V) and portability of the energy harvester, the capacitor value of 13200μF is chosen. As such, a schematic electronic circuit is displayed in Figure 9. The circuit was constructed and further tested with a AC sine wave voltage source and two 1.5V LED at the load output. The frequency of the LED blinking decreased as the total capacitance increased. As expected, only with a capacitance of 13200μF and above, the LED was constantly lit up without any observable blinking.

With a voltage output maintaining above 2.4V in place, it is crucial that the circuit is optimised for higher current to ensure faster charging. Hence, the rectifier circuits attached to each induction coil is then connected in parallel, such that each branch contributes to the total current used to charge the battery.

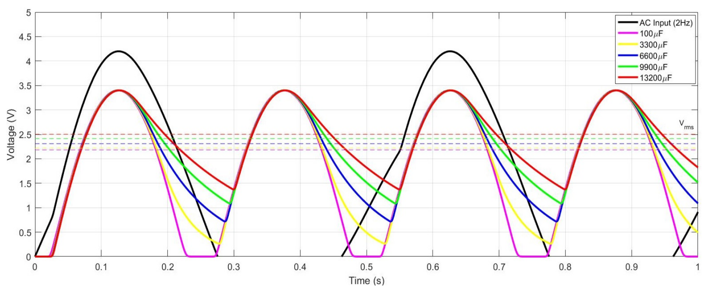

Figure 7: LTspice Simulated output voltage of full wave rectifier with smoothing capacitors of values 100μF, 3300μF, 6600μF, 9900μF and 13200μF given an input AC voltage source with a sine curve at amplitude 5V and frequency 2Hz.

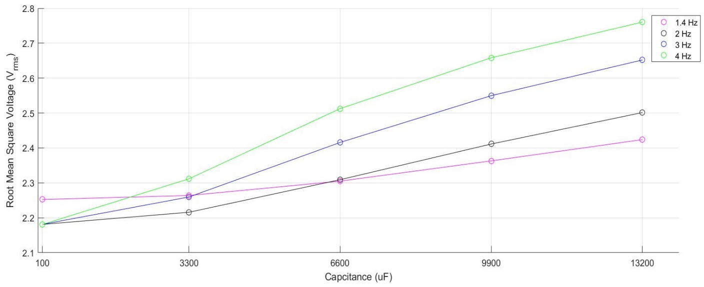

Figure 8: LTspice Simulated Root Mean Square voltage output of full wave rectifier with smoothing capacitors values of 100μF, 3300μF, 6600μF, 9900μF and 13200μF, at varying input AC voltage source frequencies of 1.4, 2, 3 and 4 Hz.

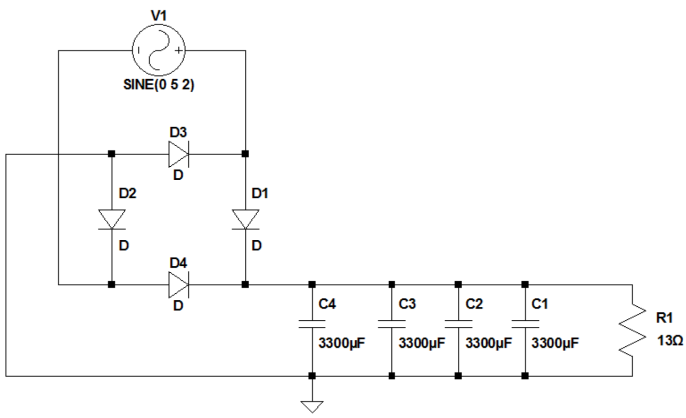

Figure 9: Schematic outline of electronic circuit, consisting of a bridge full wave rectifier and 4 smoothing capacitors of total capacitance 13200μF.

5. Experimental Methods

5.1. Preliminary experiments

To investigate the voltage and current output of prototype (c) and (d) in Figure 3 at different frequencies, both prototypes were subjected to a vibration at an amplitude of 12cm. The vibration caused by manual shaking with hands and the frequency was determined by the number of oscillations in 30 seconds. The frequencies used ranged from 1 to 4 Hz. The voltage and current were measured with a multimeter. However, it should be noted that small variations in the results might arise due to the inability to accurately fix the frequency.

To investigate the electrical output of different coil wire diameters, a similar experiment using prototype (c) was conducted at 4 Hz and 12cm for coil wire of diameters 0.2mm (1500-1700 turns per coil) and 0.5mm (500-600 turns per coil).

5.2. State of charge of battery

To measure the state of charge of the battery, the battery was characterised by discharging. By measuring the potential difference across it at time intervals of 20 minutes and comparing the potential difference value between periods of charging, the discharging curve of the battery was acquired. The discharge parameters were obtained by discharging a 1.2V battery across a 10 Ω resistor as shown in Figure 10. A low resistance was chosen to hasten the discharging.

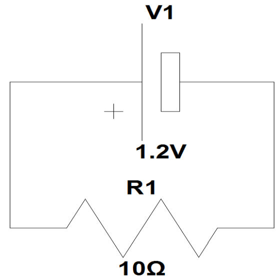

Figure 10: Schematic Outline of experimental set-up in characterising the discharging and charging curve of a battery.

After obtaining a discharge curve, the battery performance could be measured by taking the difference of the potential before and after the battery is charged. The state of charge of the battery (Figure 13 in Section 6) was derived by plotting the ratio of the area under the charging curve in 20 minute intervals to the total area under curve.

5.3. Performance of Energy Harvester

While the potential generated by the energy harvester could in theory charge as much as three batteries, the performance of the energy harvester is characterised with the charging of one 2800mAh Ni-MH 1.2V battery. By simplifying the characterisation to a single battery, the possibility of unequal charging of multiple batteries, which results in inconsistent values of large variation, can be eliminated.

In preliminary experiments, the energy harvester was tested on an ergonomic machine to harvest the energy from the movements. However, upon actual testing of the product, energy generated from these machines were relatively insignificant as compared to those generated when running on the treadmill. This was due to the need for relaxation of the person during the intensive workout. While the initial pulling force generated a substantial amount of vibration and amplitude, the recovery of the exercise failed to provide a consistent frequency that was crucial for energy generation by electromagnetic induction. In contrast, it was observed that in both recovery and exerting phases, there were consistent vibrations of the magnets in the tube.

The energy harvester is to be velcro-strapped at the side of the runner's feet, parallel to the ground. The initial potential difference across the battery is 0.02V. Measurements of the potential difference across one 1.2V battery is taken at intervals of 3 minutes after running a distance of 400m at a constant speed of 10km/h on the treadmill. The runner rests for 1 minute before starting another set of 400m run. Within the 1 minute, it was observed that the battery was still charging due to the discharging effects of the capacitors in the electronic circuit. The action of running is assumed to be periodic. The range of amplitudes (length of stride) and frequency of motion are calculated to be 70 to 98 cm and 1.3 to 1.5Hz respectively. The frequency was obtained by counting the number of strides in a minute. In addition, measurements of the instantaneous voltage output of the energy harvester is recorded as well. This will aid in calculating the energy equivalent watt-hour output of the energy harvester.

6. Results and Discussion

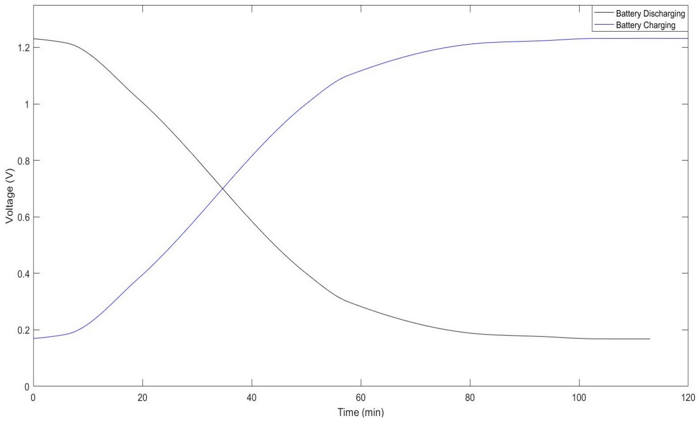

Figure 11: Charactersation of the 2800mAh Ni-MH 1.2V battery charging and discharging curve.

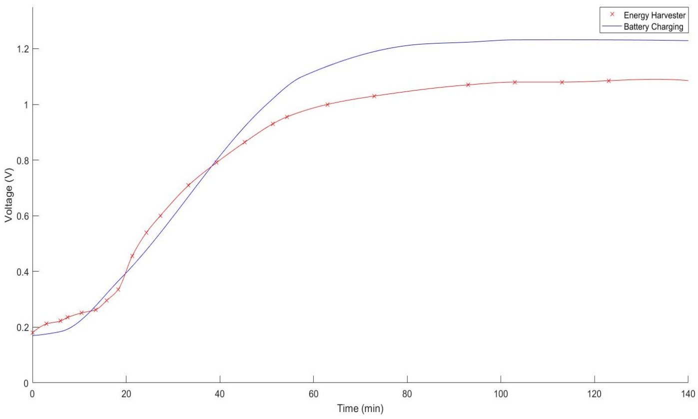

Figure 12: Comparison of characterised battery charging curve with energy harvester's charging curve.

From Figure 12, there was an increase of 1.08V within 93 minutes of charging, by running at 10km/h in a total distance covered of 8km. This translates to a 91.64% increase in the potential difference across the battery. Given that the voltage across the energy harvester fluctates from 2.4V to 3V within the 20 minutes, the minimum and maximum watt-hour generated at every 20 minute interval is drawn out in Table 2. The watt-hour values are derived by taking a fraction of the total 2800 mAh capacity of the battery and multiplying it by the lowest and highest voltage possible. Due to the characteristics of the charging curve of the battery, the battery at low potential difference requires a longer charging time to increase in its capacity. Hence, this explains the lower watt-hour output for the values before 40 minutes of charging. Above 40 minutes, the watt-hour values are similar with small variations, which are operating in the near linear region of the charging curve. As such, the mean with S.D. of values above 40 minutes is calculated in Table 3.

Comparing the maximum total watt-hour of 7.837Wh to a typical 5000mAh battery at 5V that produces 25Wh, there is much to work on in terms of its portability and output. However, given that the energy harvester is constructed of a few magnets and coils, it serves its purpose as a self generated power souce for emergency usage that can harvest energy from

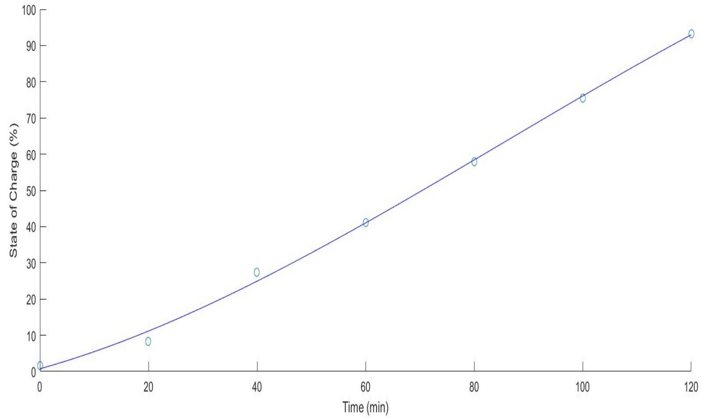

Figure 13: State of charge (%) against time (min) by the energy harvester.

Time (min)	Minimum (Wh)	Maximum (Wh)
20	0.112	0.140
40	0.450	0.563
60	1.273	1.591
80	0.931	1.164
100	1.126	1.407
120	1.186	1.482
140	1.192	1.490
Total	6.270	7.837

Table 2: Minimum and Maximum watt-hour generated by energy harvester at 2.4V and 3V respectively, in 20 minute time intervals.

movements such as running. The watt-hour obtained can be said to be reasonable, despite having much to still improve on.

7. Conclusion Improvements

This paper discussed the fabrication process energy harvester based on design considerations and later using trial and error to conceive the final prototype. Various applications centered around equipments in the gym were tested and it was concluded that the energy harvester best suited the application of running on the treadmill. The minimum and maximum watt-hour of the energy harvester operating in the linear charging curve range is 1.142±0.129Wh and 1.427±0.161Wh in 20 minute intervals at 2.4V and 3V respectively. The total minimum and maximum watt-hour in 93 minutes is 6.270Wh and 7.837Wh. The results are in line with our expectations as they were guided by design principles, theoretical concepts and calculations.

While the prototype generated a respectable amount of energy at 1.4Hz and over a distance of 8km with rest intervals, there was also much to improve on. The inclusion of springs as a restoring mechanism was explored in the paper but it proved to be inconvenient for the design setup. However, having springs as a restoring force would indeed further improve the electrical output. Thus, alternative restoring mechanisms, such as ones of a non-magnetic material could be considered. Also, the comfort of the prototype over long periods could be increased. Often, due to the protruding areas of the prototype, the prototype was uncomfortable to use,

	Minimum (Wh)	Maximum (Wh)
Mean	1.142	1.427
S.D.	0.129	0.161

Table 3: Mean and S.D. of minimum and maximum ower generated by energy harvester at the near linear region of the charging curve, in 20 minute time intervals.

especially after a prolonged period of time. Better ergonomics and cushioning could be implemented in further prototypes. In addition, miniaturisation of the prototype was also considered during the design stages to improve the comfort and portability of the energy harvester. However, due to cost considerations as well as the output of the harvester, there was a limit as to how small the energy harvester could be.

The energy harvester has proved to serve its purpose in being able to charge up a single 1.2V battery, with the potential to safely charge up to two batteries. The total energy generated from the energy harvester within a 8km is a modest value, however its applications can be extended to many other areas. Given its potential can to charge up to three batteries, more work has to be done to optimise the current output instead, to increase the charging rate.

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