Development of a Low-Cost Energy Harvesting Floor Tile that Operates from Footsteps

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Abstract*— This paper presents the designing and fabrication of a low-cost energy harvesting floor tile that harnesses kinetic energy available in human footsteps. The means of harnessing energy is done by use of several mechanisms such as rack and pinion, shafts, two-way to one-way rotational convertor, and an electric motor which is used as a generator to harness the useful energy to be implemented in electrical appliances. This technology can be implemented in office spaces, crowded areas and can also be integrated into Smart City concepts with great occupancy patterns and intensity. Available models in the markets are expensive and are manufactured by foreign companies. As a result, adopting an efficient and low-cost approach would be beneficial to the Sri Lankan context. The theoretical aspects of the project model design, material consideration of components, motor selection, fabrication, and testing of the designed tile are delineated in the paper. The comprehensive material selection technique has enabled the determination of the most suitable material using Multi-Criteria Decision Making (MCDM) and the ELECTRE III method. The calculated cost per watt of the designed model is 22.50 USD per WATT, which is lower than the available models. This technology can be furnished as per requirement considering flooring area, environmental conditions, and implemented in office spaces, crowded areas and be integrated to Smart City concepts.*

Keywords**—Footstep power generation, Low-cost power generation, Renewable energy, Two-way to one-way rotational convertor**

I. INTRODUCTION

Sri Lanka spends a considerable amount on the importation of fossil fuels and is highly dependent on them. Even though renewable energy harvesting technologies are penetrating the country, it is relatively at a slow rate. Harvesting energy through human footsteps is relatively a new concept in the world and the technology is being rapidly developed. This technology is yet to penetrate the country and the models already available in the market are costly. The development of an efficient and cost-effective energy harvesting floor tile will not only save money but will be able to generate a considerable amount of power locally in selected locations. This technology can also be used in developing 'Smart City' concepts as well.

The overall aim of this project is to develop a low cost, efficient, and implementable power-generating floor tile, with the objectives of designing and fabricating an energy harvesting floor tile that can harvest kinetic energy in a footstep and to test and optimize the designed tile.

II. METHODOLOGY

A. Literature Review

When considering the walking of an average person, the amount of energy produced from the striking of the heel varies between one to five joules or two to twenty watts per step (Jintanawan et al., 2020). The most common mechanisms used to harness this power from footsteps are:

1) Using Piezoelectric Materials: The capability of some materials to produce an electric potential under the influence of mechanical stress is known as piezoelectricity. These materials fall under a group of ferroelectric materials which are found as crystals and are polar without the presence of an electric field. The most common piezoelectric ceramics are PbTiO3, PbZrO3, PVDF, and PZT, out of which the latter two are the most commonly available (Poddar et al., 2017). There are two methods currently being practiced using piezoelectric materials to generate power from footsteps;

a) Using a piezoelectric cantilever
b) Using piezoelectric membrane

In the first method, a piezoelectric bimorph strip is overshot using a holder which is connected to the tile's cover plate. To obtain increased deformation, a proof mass is connected to the free end of the strip. When the tile is pressed down, the piezoelectric strip will deform due to the vibration, and the proof mass will then help in increased oscillations. Due to the deformations in the strip, an electrical charge is produced (Isarakorn et al., 2019; Panthongsy et al., 2019). Studies (Panthongsy et al., 2019) had shown that the system could be easily configured with a simple structure and that the electrical energy output had been directly proportional to the excitation force from the footing. Power can be generated from both loading and unloading of the force.

In the later method, piezoelectric membranes (discs) are connected in a series-parallel manner in the form of an active matrix and the compressive stress from the footstep is transmitted to the spacer at the centre of each disc forcing the piezoelectric material to deform and produce charge (Puscasu et al., 2018), and had shown that preloading of the piezoelectric discs have resulted in increased energy output and density (by 5.7 times in terms of stored energy).

2) Using Electromagnetic Generators: There are two methods: linear oscillation to electrical energy and rotation to electrical energy. The first mechanism needs a much larger amplitude to produce electricity. Since the vibration of footsteps of a person has a low amplitude, the second mechanism is much more efficient where the vertically downward motion of the pressing force of the footstep is converted to rotational motion and this rotary motion is then used to actuate an electromagnetic generator to produce electricity. There are two methods that had been used by researchers to obtain this rotary motion (Jintanawan et al., 2020):

a) Rack and pinion configuration
b) Lead-screw configuration

3) Current models available in the market:

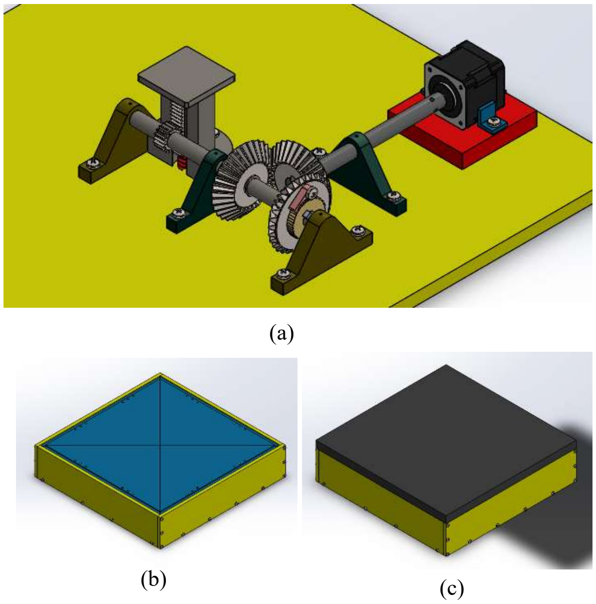
The following table shows the amount of generated energy, tile size and the market price of currently available companies/technologies (Elhalwagy et al. 2017; Solban et al. 2020).

Table 1. Available models and their prices.

Company-Technology	**Generated Energy**	**Tile Size**	**Market Price per Tile (USD)**
Waynergy Floor	10 W/step	40 x 40 cm	451.5
Pavegen tiles	5 W	50 x 50 cm	160
Sound Power	0.05 W/step	50 x 50 cm	270.9
PZT ceramic	0.0084 W	Manufacturing in small sizes	36.1

B. Experimental Design

From further analysis of previous works done, it had been concluded that the rack and pinion method of power generation is the most optimum as the rotating speed of the shaft can be increased by simply adding in a gear train. In the lead screw mechanism, there is a larger resistance to the vertical motion, and it must be designed under overhauling conditions. The tiles made using piezoelectric materials have much lower power yielding and their lifetime is also much lower as the membranes tend to deteriorate much faster when compressed repeatedly.


(a)

(b)

(c)

Figure 1: (a) Internal components of the conceptual design, (b) With the intermediate layer, (c)Final product (CAD).

A conceptual design (Figure 1 (a), (b), and (c)) had been made using the rack and pinion mechanism including novel mechanisms to increase the power-yielding capability

C. The Two-way to One-way Rotational Convertor

In all the mechanical designs in the literature, using both rack and pinion and lead screw mechanisms, the output shaft rotates alternately in clockwise and counterclockwise directions. This leads to some losses in the power transmission, as it takes some energy to reverse the momentum of the shaft. To eliminate this, a two-way to one-way rotational convertor (Figure 2) had been introduced in this design.

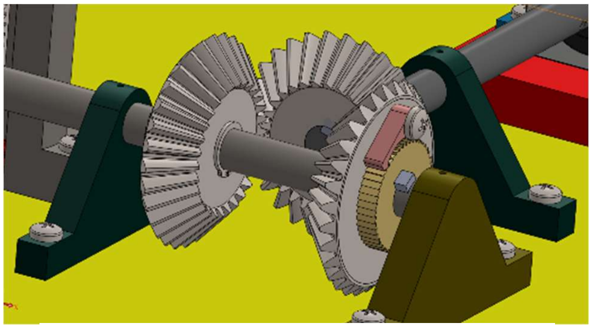


Figure 2: The two-way to one-way rotational convertor.

Using this (Figure 2) mechanism, the two-way rotation created by the upward and downward motion of the rack can be converted into a continuous rotation in one direction.

D. The Intermediate Layer

In the designs mentioned in the previously discussed literature, there is a sudden drop in the top tile layer to get a vertical displacement (Isarakorn et al, 2019; Panthongsy et al, 2019; Puscasu et al, 2018; Jintanawan et al, 2020). But in the real world, this sudden vertical drop can cause an uncomfortable feeling for pedestrians as it is not motion anyone comes across in day-to-day walks. To reduce this uncomfortable feeling, an intermediate layer had been introduced which consists of four right angular triangles, hinged to the four sides of the tile. Hence when the foot presses down the tile surface, it caves inwards pushing down the rack, rather than a sudden drop in elevation.

E. Inclusion of a Stepper Motor

Stepper motors spin the shaft in angular increments that correspond to discrete signals supplied into a controller. They can have inputs that are either AC or DC. The motor functions as an incremental actuator, converting digital pulses into analog shaft rotation. The speed of rotation is dependent on the pulse rate and the incremental step angle. (Scarpino, 2016). The smaller the motor's step angle, the greater its angular resolution. A stepper motor is expected to hold its position when it comes to a halt, and holding torque identifies the maximum torque it can exert to maintain its position. When used as a generator, the output is an AC voltage and is converted to DC by using bridge rectifiers.

F. Comprehensive Material Selection

1) Gear Material Selection: The material selection for gears had been a crucial component since it affects the transmission of power, longevity of the product, and the cost of the product directly. A comprehensive analysis had to be done with the use of a mathematical model utilizing a Multi-Criteria Decision Making (MCDM) considering the different performance indices (Table 2) that affect power transmission, strength, and the cost of different materials that are used to manufacture gears.

Table 2: Performance indices.

Performance Index	**Equation**	**Min/Max**
g1	S_{fe}	Max
g2	UTS/S_{fe}	Max
g3	$S_n' C_s$	Max
g4	UTS/S_n'	Max
g5	H_{core}	Min
g6	ρ (density)	Min
g7	C (cost per kg)	Min

Then the ELECTRE III method had been used to solve the MCDM problem (Table 3) to obtain the most optimum material. Hence for the manufacturing of these gears, mild steel had been chosen which can be carburized due process.

Table 3: ELECTRE III results.

Material	**Net Superior Value**	**Rank**
Cast Iron	-5.396	9
Ductile Iron	-4.564	8
S.G. Iron	-1.317	6
Cast Alloy Steel	-1.107	5
Through-Hardened Alloy Steel	2.188	4
Surface Hardened Alloy Steel	3.326	3
Carburized Steel	6.801	1
Nitrided Steel	3.597	2
Through-Hardened Carbon Steel	-3.529	7

2) Housing Material Selection: It had been decided to make the tile housing with reinforced plastics due to its low weight and high strength. TECATEC PEEK MT CW50 had been chosen as the material for the tile base, housing, and intermediate layers.

G. Finite Element Analysis

Static analyses were conducted on the components (Figure 3). A mesh size of 0.5 mm had been used due to constraints in computational power. Von-mises failure criteria had been used to analyse the failure as is widely accepted for ductile materials. It had been observed that the designed components are able to withstand the stresses generated. It showed that all the components are within safe limits.

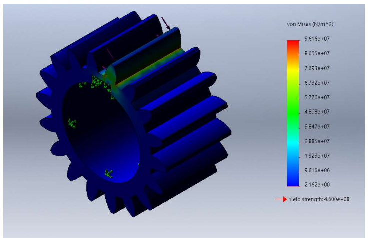


Figure 3: Static analysis of spur gear.

The fatigue analyses give a closer look into the fatigue failures that could occur in the design when considering the long-term operation of the components as the system is loaded and unloaded consistently when in use. From the fatigue studies conducted for critical components, it had been observed that the minimum loading factors are all above 1, implying that the design is safe from fatigue failure for 1,000,000 cycles of static loading. This can further be increased by proper lubrication and maintenance. The buckling analyses conducted for the required components also gave results with safe buckling load factors.

H. Simulink Modelling

MATLAB Simulink had been used to model the operational systems of the project (Figure 4) assembly to

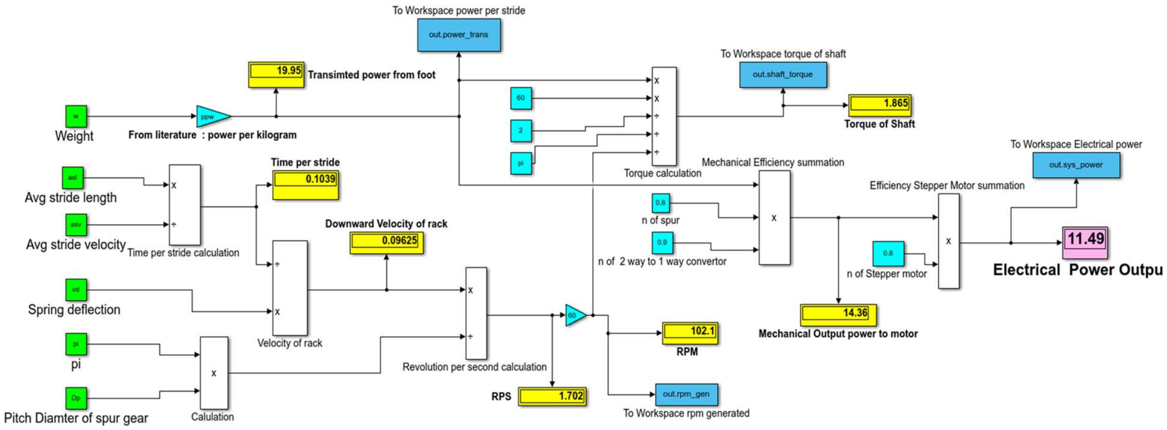
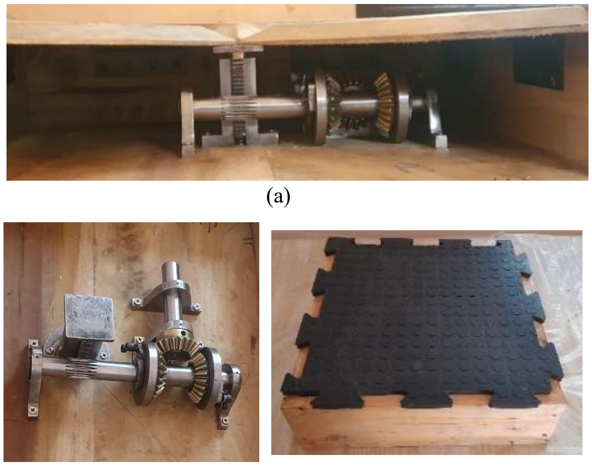


Figure 4: Simulink Model

automate theoretical data calculations with variable inputs, and after fabrication, compare data findings and increase the system's efficiency. It can be used to understand where the system's efficiency is lagging in the fabricated model and make changes accordingly.

I. Fabrication and Assembling of Components

Figures 7, 8 & 9 show the assembled components. Instead of a spur gear, the input shaft diameter had been increased to 20 mm and splined to meet the requirement. The bevel gears had been changed from module 2 to 2.5, no of teeth 30 to 25, and bore diameter 12 mm to 20 mm, which were already available, hence reducing manufacturing time. Output shaft diameter had also been increased to 20 mm due to changes in bevel gears. The gears, shafts, shaft brackets, ratchets, and pawls had been fabricated from Mild Steel. For the Tile Base material, wood (*Mahogany*) had been used instead of reinforced plastics due to ease of machinability and low cost.



(a)

(b)

(c)

Figure 5: (a) Inclusion of the intermediate layer, (b) Assembled components, (c) Final Product

III. RESULTS

A. Laboratory Testing and Results

Testing had been conducted to take a more in-depth look at the functioning, efficiency, and power generated, prior to the full completion of the model with the intermediate layer and top cover to ensure that the most optimum model goes inside the tile.

Several components of the mechanical and electrical models had been varied to get the most optimum configurations and the results are shown in Table 4 and Table 5.

Table 4: Results using NEMA 17 stepper motor.

		Spring Deflection					
		10 mm		**20 mm**		**30 mm**	
		V	**A**	**V**	**A**	**V**	**A**
Capacitor Variation	**330 μF (10 V)**	8-10	0.07	9-12	0.1	11-14	0.2
	680 μF (25 V)	6-8	0.07	9-12	0.1	12-15	0.2
	1000 μF (25 V)	6-8	0.08	9-11	0.1	13-15	0.2

Table 5: Results using NEMA 23 stepper motor.

		Spring Deflection					
		10 mm		**20 mm**		**30 mm**	
		V	**A**	**V**	**A**	**V**	**A**
Capacitor Variation	**330 μF (10 V)**	7-10	0.1	9-13	0.3	11-13	0.5
	680 μF (25 V)	11-13	0.2	15-17	0.3	16-18	0.5
	1000 μF (25 V)	10-12	0.3	10-17	0.5	17-23	0.7

B. *Field Testing and Results*

Several candidates had been asked to walk on a ramp (Figure 6), which is to the height of the tile. Then, the candidate had been interviewed about their experience and any difficulties they faced.

Figure 6: Field testing set up with a ramp.

Few comments on their experience are as follows:

- "No discomfort"
- Recommended for stepping exercises in a gymnasium.
- "Felt afraid the 1st attempt."
- "Not that much of a problem on the 2nd attempt"
- "No discomfort when stepping on the center."
- "A bit uncomfortable when stepping towards the side."
- "Afraid to step on it."
- "Felt uncomfortable"
- Recommended for the university cafeteria entrance.
- "Put a sign to inform people before they step on it."

The voltage generated by each candidate had been recorded (Figure 7). Each candidate was given two attempts to walk and step on the tile.

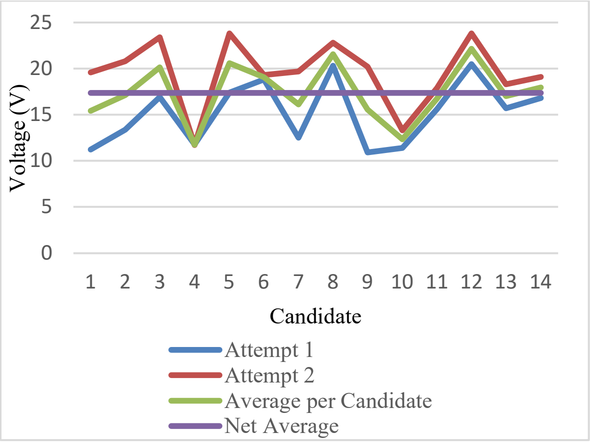


Figure 7: Generated voltages.

C. *Cost per Watt*

Average power generated from the tile = 18 V X 0.7 A
= 12.6 W
Efficiency = (12.6 W/20 W) X 100% = 63%

Total cost for the model = Rs. 83,297.00/=
= $ 227.00/=
Cost per Watt for model = **$ 18.00 per Watt**

Estimated total cost for the prototype = Rs. 104,467.00/=
= $ 284.00/=
Estimated cost per Watt for prototype = **$ 22.50 per Watt**

IV. DISCUSSION

The unique additions in the design are the inclusion of an intermediate layer, the inclusion of a two-way to one-way rotational converter, and the inclusion of a stepper motor. The MCDM procedure along with the ELECTRE III method for the material selection had been a great tool in succeeding at this task, minimizing the errors that could have happened due to lack of expertise in making a proper judgment when selecting gear material. This mathematical methodology can be used in many engineering applications where proper selection of material is vital.

During the Laboratory Testing phase, it had been noted that the power generated increased with the increasing downward deflection and with the intensity of the downward force and there is an effect on the discharge time with the variation of the capacitors used. A downward deflection of 30 mm had been allowed in the model for field testing. From the Field-Testing phase, it had been identified that the power generated by a footstep depends highly on the speed of walking, body weight, mental preparation for the downward deflection of the foot, curiosity to step on it, mental state on comfortability, type of footwear and enthusiasm for the concept of "Power generating floor tiles."

To carry out an ROI for the design, further studies must be done on the daily, weekly, and monthly available density of people in the selected specific area, specific routes and pathways often used by people, studies on social acceptance and comfort levels and willingness to walk on pathways created by power generating tiles.

V. CONCLUSION

A. *Conclusion*

The designing, fabricating, and testing outcomes of a low-cost energy harvesting floor tile that operates from footsteps were proposed in this paper. The use of rack and pinion to convert the vertical motion to rotational motion, which then goes through a two-way to one-way rotational convertor is fed to the stepper motor which acts as a generator. Next, a rectification circuitry had been incorporated for the generated AC output. In the designing process, the use of MCDM procedure along with ELECTRE III method had been integrated, stress calculations and FEA had been conducted on the designed components. The theoretical results showed that the designed model was feasible to be fabricated and perform efficiently.

The Cost per Watt comparison of the designed tile with the available models in the market is shown in Table 6.

Table 6: Cost per Watt Comparison

Company / Technology	Generated Energy	Price (USD)	Cost per Watt (USD per W)
Waynergy Floor	10 W per step	451.50	45.15
Pavegen Tiles	5 W	160.00	32.00
Sustainable Energy floor	7 W (average)	1,693.00	241.85
Sound Power	0.1 W per step	270.90	2,709.00
PZT ceramic	8.4 mW per step	36.10	4,297.61
Designed Model	12.6 W (average)	284.00	**22.50**

Hence the aim and the objectives of this study had been successfully met.

B. Future Works

1) Cascade connection with a Battery Management System: To provide a steady flow of power to the appliances it must be first stored in a battery pack. A Battery Management System (BMS) must be used for this. But it is currently beyond the expertise of the authors.

2) Inclusion of a Gear Ratio: The mechanical design in this project make use of a two-way to one-way rotational convertor incorporating bevel gears. Since this is the first-time making use of such a system, the use of a gear ratio in transmitting rotation from the input shaft to the motor shaft had not been done due to doubts on whether the system would work as intended or not. Considering the real-world actuation of the fabricated mechanism, a gear ratio can be implemented to enhance the yield, constrained to the specific contextual requirements of the application.

C. Applications

Proposed applications of the designed power generating floor tile are pedestrian pavements, entrances and exits, office pathways, bus stations, train stations, airports, and gymnasiums.

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