Feasibility on development of kinetic-energy harvesting floors

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Abstract. Electricity consumption in big cities has been increasing, especially in crowded areas. Although there is a large amount of energy usage in such places, people can generate the unnoticeable electrical energy from their footsteps. This paper aims to present the feasibility on development of an energy harvesting floor—called Genpath—using a rotational electromagnetic (EM) technique to generate electricity from the human’s footsteps. The system in Genpath comprises two main parts: the EM generator and the power management and storage circuit. After stepping over the floor, a rack-pinion mechanism under the floor converts the linear translation from a footstep into the rotation to drive a DC-generator to generate electricity. The EM generator yields an average energy per footstep of about 199 mJ (or average power of 331 mW) and the maximal voltage of 19 V at the rated 140-Ω load resistance. This amount of energy is sufficient for low power consumption electrical devices. The efficiency of the EM generator in Genpath is 16.6% based on the power generation from the heel strike of the human’s walk of 2 W per step. Among overall energy generated by the generator, 68% of generated energy is stored in the 9-V rechargeable batteries and the rest is supplied to the 4-V, LED instantaneous loads. The power management and storage circuit consisting of the diodes and DC-DC buck voltage converters was successfully designed. With 54% efficiency of the circuit, the average energy per step of 169 mJ can be stored in the rechargeable battery, and the other 4.7 mJ can be supplied to the LED loads.

1. Introduction
Electricity consumption in Thailand was ranked 22nd of the world with the rate of 1.64×10¹¹ kW-h per year [1]. The consumption rate has been increasing for years, especially in the big cities where the crowded people exist such as the airports and public stations, the commercial buildings, and the department stores. Seeking an alternative energy in such crowded areas, noticeable that a large population can generate the power from their footsteps. Therefore, an ultimate goal is to develop an affordable Vibration Energy Harvesting (VEH) system—called Genpath—the smart floor capable of converting kinetic energy from those thousands of footsteps into electrical energy for further use. Genpath can be installed in places with a crowded population for harvesting energy.

Energy harvesting from human motions is currently an interesting and applicable issue, thanks to the ultra-low power consumption of electronic devices lately [2]. Focused on walking, the energy produced by the heel strike of people’s walk is 1-5 J or 2-20 W per step [3]. There are various commercial products that harvest energy from people’s walks, such as energy storage shoes [4] and the energy floor [5]. However, few technical details of those products are published thus far. Therefore, the objective of the paper is to design a simple but efficient VEH floor embedded with the
electromagnetic (EM) generator. Furthermore, performances of the sub-systems were analyzed and tested in this paper.

2. Review of the energy generating techniques in VEH

Kinetic energy comes in various forms, e.g., seismic noise, vibration of rotating machinery, motions of vehicles and human, etc. Vibrational energy harvesting (VEH) is the concept of conversion of those kinetic energies presenting in the environment into electrical energy. There are two main techniques of kinetic-to-electrical energy conversion applicable to the design of the VEH floor: i.e., piezoelectric generator and electromagnetic generator [6]. The piezoelectric generator produces an electrical charge and energy when deformed under mechanical stress. Piezoelectric generators can provide high voltage levels up to several volts. With its compact size, the piezoelectric generator gives high power density per unit of volume [7]. The electromagnetic (EM) generator generates an electromotive force (EMF) and thus energy when the permanent magnet relatively moves through the coil. Both techniques of VEH discussed are suitable for generating energy for low-power electronic instruments. However, the piezoelectric generator effectively gives out maximum energy at the frequency bandwidth around its natural frequencies, i.e., higher than 200 Hz, whereas the bandwidth of human motion is between 1-10 Hz. In contrast, the electromagnetic generator is effective in the frequency range of 2-20 Hz. Hence, it is more suitable for harvesting energy from human movements. In addition, the electromagnetic generators also yield higher power density and their costs are much lower than the piezoelectric generators [8].

There are two different EM generators in terms of energy-conversion mechanisms: linear oscillation to electrical energy and rotation to electrical energy [9]. The mechanism of linear oscillation conversion is simpler, but it requires the larger amplitude of excitation to produce electricity, whereas human pedaling is random in vibration with low amplitude. Thus, the rotational EM generator is chosen to convert kinetic energy from people’s footsteps into electrical energy. For simplicity, a direct (DC) generator is used in the design. In operation, a rack-pinion mechanism is adopted to convert a linear motion from a human’s pedal to a rotation of the rotor to drive the DC generator.

3. Design of subsystems

The VEH floor—called Genpath—capable of harvesting kinetic energy from people’s footsteps and converting it to electrical energy was developed. The system consists of two main parts: 1) the system of the EM generator and 2) the system of power management and storage circuit.

3.1. The system of the EM generator

3.1.1. Conceptual design. In the process of energy generation, the rotational-EM generator is deployed as it is independent from the resonant frequency and capable of achieving higher energy density compared to the linear EM generators. Figure 1 shows the design drawing of the generator system in Genpath. A rack-pinion mechanism is decided to convert the rack’s translation from a step to the pinion’s rotation. The pinion then drives the DC-generator shaft through the gear train, which transforms low-speed power to high-speed power. With rotation of the generator, the electrical current can be generated. In addition, to restore the rack back to the equilibrium position, the lower end of the rack connects to the springs. The whole system limits by the space of 10×10×20 cm³ and the maximum displacement of 2 cm, therefore the small size of 12-24 V-DC motor is used as a DC generator. To generate more energy within the limited displacement and space, the maximum gear ratio of 4:1 is designed, originated from a pinion’s 6-cm diameter transmitted to a gear’s 1.5-cm diameter as shown in figure 1.

In order to generate at least 3.3 V for operating the micro-controller, the typical 24-V DC motor generator was selected to ensure such criteria. To choose a proper DC generator’s speed, the kinematic relation of the transmission system is analyzed. With the maximum value of 2.0-cm displacement for safely walking, the maximum value of the angular velocity is obtained at 210 rpm. Hence, the model of a 24-V DC motor generator with a 300-rpm rated speed is selected.
3.1.2. Analysis.

To predict the energy performance of the EM generator design, the dynamic model of the electromechanical system in 3.1.1 is developed using Matlab®/Simulink. Figure 2 shows the physical model of the system comprising the elements of rack, pinion and gear train on mechanical side, and the DC generator (with its own resistance $R_G$ and inductance $L$) connected to the load $R_L$ on electrical side. The footstep force $F(t)$ is modeled as a ramp function with a magnitude of 800 N within 0.6 s. The spring with a maximum compression of 20 mm and a stiffness coefficient of 350 N/m provides the restoring force $F_s$ to restore the rack back to the equilibrium position.

The state equation governing the electro-mechanical model is

$$\begin{align*}
\frac{d}{dt}\begin{bmatrix}
i \\
x_1 \\
x_2
\end{bmatrix} &=
\begin{bmatrix}
0 & K_t & 0 \\
0 & -\frac{K_t}{L} & 1 \\
0 & -\frac{K_t}{M} & C_m
\end{bmatrix}
\begin{bmatrix}
i \\
x_1 \\
x_2
\end{bmatrix} +
\begin{bmatrix}
0 \\
0 \\
-F_s + F(t)
\end{bmatrix}
\end{align*}$$

(1)

where the state variables $i$ is the current, $x_1 = x$ is the displacement and $x_2 = \dot{x}$ is the velocity. In addition, in (1), $M = (m + \frac{J_p}{r_p^2} + \frac{J_G}{r_p^2})$ is the equivalent mass corresponding to the mass of the rack $m$, and the mass moments of inertia of the pinion and gear $J_p$ and $J_G$, respectively. In (1), $C_m$ is the viscous damping in the mechanical system. Also $L$, $R_G$ and $K_t$ are the inductance, resistance and back emf (torque) constant of the DC generator, respectively.

A Simulink model corresponding to (1) was developed to predict the performance of the EM generator system with the designed parameters in 3.1.1. The simulation results are illustrated in figure 3 and summarized in Table 1. The results mainly show that the designed system generates an averaged 215 mJ of electrical energy per footstep which is sufficient to power the electronic devices with low power consumption in the vicinity area such as sensors and communication instruments. This finding assures the possibility of building Genpath’s prototype in the next step.

3.1.3. Development of the prototype.

Figure 4 shows the prototype built with the key components, as described in 3.1.1. The experiment was then performed to test the prototype’s performance. First, the prototype was connected to a 140-Ω rated resistor $R_L$ to provide the maximum power output. Then the voltage across $R_L$, the current $i$ and the corresponding electrical power when a normal footstep applied were measured using an oscilloscope and a current probe. The test results are shown in figure 5 and summarized in Table 2. It stated in Table 2 that the prototype produces an average energy of 199 mJ (or average power of 331 mW), the maximum voltage of 19.1 V and the maximum current of 131 mA per footstep in the duration of 0.6 s. The efficiency of the EM generator in Genpath is 16.6% based on the power
generation from the heel strike of a human’s walk of 2 W per step. This amount of energy could sufficiently provide for the typical low-power electrical devices, as previously described.

**Figure 3.** Simulated results of the generated voltage and current for $R_G = 50 \, \Omega$ and $R_L = 140 \, \Omega$.

| Table 1. Simulated performance of the designed EM generator system. | Table 2. Performance test of the designed EM generator system. |
|---------------------------------------------------------------|---------------------------------------------------------------|
| **Variables** | **Values per footstep** | **Variables** | **Values per footstep** |
| Maximum voltage | -26.9 V | Maximum voltage | -19.1 V |
| Average voltage | -3.86 V | Average voltage | -5.05 V |
| Maximum current | -192.0 mA | Maximum current | -131.0 mA |
| Average current | -27.7 mA | Average current | -41.8 mA |
| Maximum power | 5.16 W | Maximum power | 2.58 W |
| Average power | 358 mW | Average power | 331 mW |
| Wave duration | 0.60 s | Wave duration | 0.60 s |
| Average energy | 215 mJ | Average energy | 199 mJ |

**Figure 4.** Prototype of the generator system with key components.

**Figure 5.** Performance of the generator system in Genpath.
3.2. The system of power management and storage circuit

The circuit was designed to store and distribute electrical energy at the same time. Figure 6 shows the circuit diagram. From the performance test of Genpath in figure 5, it is clearly seen that signals of the generated voltage and current have both negative and positive parts. Negative signals occur when a footstep is applied, causing the generator to rotate in one direction. Positive signals occur during the restoration period, resulting in the opposite direction of the generator’s rotation. Hence, the electrical energy from the negative part is selected to store to a battery and the electrical energy from the positive part is used to supply to the instantaneous loads. The two diodes on the left of figure 6 help by-pass the signals. Then, the DC-DC buck voltage converters, seen in figure 6, help make the voltages supplied to the battery and make the load stable. A capacitor embedded in the DC-DC converter board also helps smooth the signal and increase the efficiency of the circuit.

![Figure 6. Schematics of power management and storage circuit.](image)

A similar test, as mentioned in 3.1.3, was conducted to test the performance of the circuit. First, with the desirable voltages of 9 V for the battery and 4 V for the load, the DC-DC buck voltage converters were set to produce a 10-V and 5-V outputs, respectively. In the test, the Genpath prototype was connected to the circuit together with the 9-V battery for the upper part and the 50-ohm loaded resistor with four LED for the lower part, as shown in figure 6. When a normal footstep applied, the currents and voltages at various stages in the circuit were measured.

In summary, when the electrical signal from the DC-generator was conditioned by the power management circuit, Genpath can produce the average energy per footstep of 169 and 4.7 mJ for the battery storage and for the LED loads, respectively. From the designed circuit, 68% of the average energy per footstep was provided for the energy storage and 32% for the load supply. The overall efficiency of the circuit is 54%. The efficiency is mainly affected by the loss of energy in the circuit components such as diodes and DC-DC buck voltage converter.

4. Installation and demonstration

To demonstrate the application of the developed system, the system is assembled as a floor tile with the dimension of 40×40×15 cm and installed by three sets of the floor tiles side-by-side without wiring at exhibition hall of 100-years engineering building, Chulalongkorn University, on the mechanical engineering project exhibition day. Figure 7 shows the photo of the system. Then the exhibitors were invited to walk on the floor tiles. Once they step on the floor tiles, the system generates the power to store in the battery and light up the array of LED, as seen in figure 7. This demonstration could make exhibitors relive the importance of green energy and energy harvesting in their daily lives. The benefit of the designed system for other applications, such as a sensor and Internet of Thing applications, could be demonstrated in future work.

5. Conclusions

The paper presented a design of energy harvesting floor capable of converting mechanical energy from people’s footsteps to electrical energy. The system, comprising the translation-to-rotation conversion mechanism, the EM generator, and the power management circuit system, generates electricity from people's footsteps. The conversion mechanism from linear translation to rotation was designed by using the rack-pinion mechanism and transmitted the power through the gear system. In the process of
energy generation, the rotational-electromagnetic generator is deployed as it is independent from the resonant frequency and capable of achieving higher energy density compared to other kinds of electromagnetic generators. A prototype of the EM generator system was successfully built, which yields an average energy per footstep of about 199 mJ (or average power of 331 mW) at the rated 140-Ω load resistance. Then the power management and storage circuit is designed to store some part of the harvested energy into the batteries and to supply the other part to specific loads for the instantaneous use. Finally, the energy harvesting floor generates average electrical energy of about 173 mJ per footstep.

![Figure 7. Installation and demonstration.](image)

Although the design prototype meets the expectation of harvesting the energy for low-power electrical devices, there still rooms for improvement so that the system can generate more energy for the storage and usage. Three recommendations are addressed here. 1) The conversion system from translation into rotation could be redesigned by using the lead screw system instead of the rack-pinion mechanism to reduce the friction loss and hence to increase the efficiency in mechanical side. 2) The power management circuit for energy storage should be redesigned so that it is more applicable to the low-power energy harvesting system, and the circuit efficiency could be improved. 3) For the future design, the displacement of 2.0 cm should be reduced by half to make people feel a natural and continuous walk.

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