

A Door Motion Energy Harvesting System for Powering an Electronic Door Lock

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Abstract

The harvesting of energy from small, unconventional sources is becoming more practical as higher density energy storage media emerge and ultra-low-power smart electronics can be integrated into the system. The act of a human opening a door can be employed as a means of generating electricity that can be captured and stored for use by electronic devices. In the application presented here, the energy required to operate a card-swipe electronic door lock is obtained from the motion of the door itself. A small hinge-mounted electromechanical generator is used to convert the rotational motion of the door into electrical energy. The output voltage of the generator is increased to that required by the door lock system with a custom DC-DC converter. The electrical output energy of the DC-DC converter is stored in a supercapacitor for use by the lock. The net energy harvested is greater than that required by the lock to perform the unlock procedure; thus the system is sustainable. In this paper, the test setup and data obtained from various door opening scenarios is presented. The electrical and mechanical design of the energy harvesting system is also presented and discussed.

Motivation

All classroom and office doors in the new engineering building on the authors' campus are equipped with electronic card access locks. Each lock is powered by six AA primary non-rechargeable, alkaline cell batteries. During the first few months of building occupancy, many of the lock batteries became exhausted. Access to these rooms was delayed until maintenance could manually unlock the doors and install fresh batteries. With primary batteries alone, this scenario is inevitable.

The challenge would be to design a lock power system that could scavenge the energy required to power the electronic lock from sources local to the door. The obvious source of energy is the motion of the door. If sufficient energy from one open and close sequence of the door could be captured, the energy required by the lock itself could be replaced such that the system was sustainable with little or no energy taken from the battery.

Introduction

Harvesting the energy from human sources has been widely presented and discussed in recent literature [1, 2]. Specifically, the energy generated by human use of doors has also been investigated [2, 3, 5, 6]. The main goal in most energy harvesting applications is to capture waste energy that would otherwise be lost or ignored. When capturing human energy, the goal is often to make the process invisible and thus not unusually burden the user. In the situation presented here, the door user should not experience any unusual operation of the door as a result of the energy harvesting apparatus.

The types of doors investigated in this work are common swing doors with no closing mechanism of any kind. The user must physically push the door open and shut. Each door is equipped with a card-swipe electronic entry system as shown in Figure 1.



Figure 1. Photos of electronic lock assembly, inside and outside view

The typical entry sequence involves swiping a badge through the card reader on the outside of the door, turning the handle, pushing the door open, and then pushing it closed from the other side. In the office scenario, the door is often left open until the user leaves the room rather than closing it immediately after room entry. Thus, there might be only one opening and closing of the door between subsequent unlock operations.

A simple hinge-mounted rotary motor functioning as a generator was conceived as the energy harvesting device. If the motor shaft could be made coaxial with the door hinge axis, a simple mounting arrangement could be implemented. The motor shaft could be fixed to the stationary side of the hinge while the motor housing could then be mounted to the door to provide the required relative motion between the shaft and housing. The wiring from the generator to the lock assembly would then be all contained on the door itself. Figure 2 shows a photograph of the generator mounted to the door.

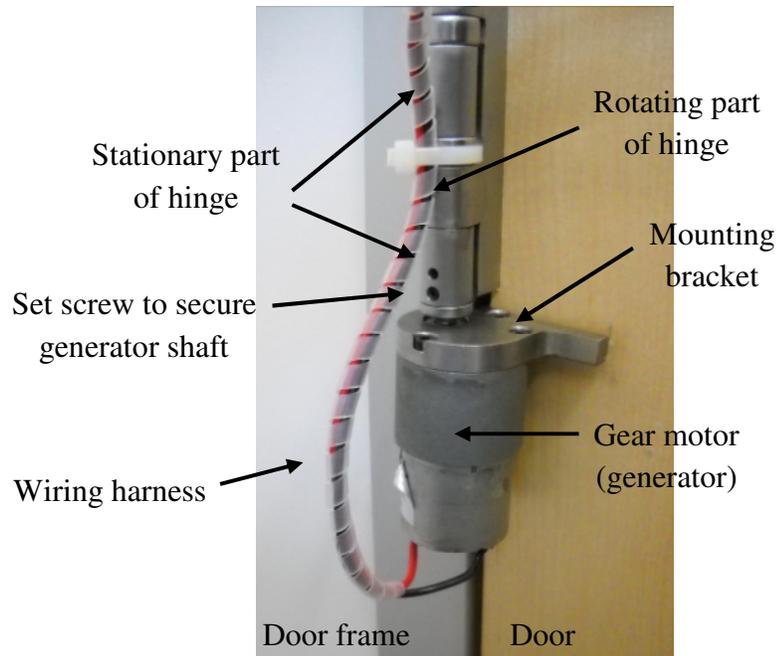


Figure 2. Photograph of energy harvesting unit mounted to door

Due to the relatively slow door rotation speed, a gear motor was required to provide sufficient motor speed to produce useful output voltage levels. Gear motors typically have the final output shaft offset toward the edge of the housing which also helped to facilitate aligning the shaft with the hinge axis.

Energy Considerations

The energy required by one unlock sequence was measured to determine the system design minimum. The lock unit's battery output current was recorded during a card swipe unlock sequence. Figure 3 shows the recorded current waveform.

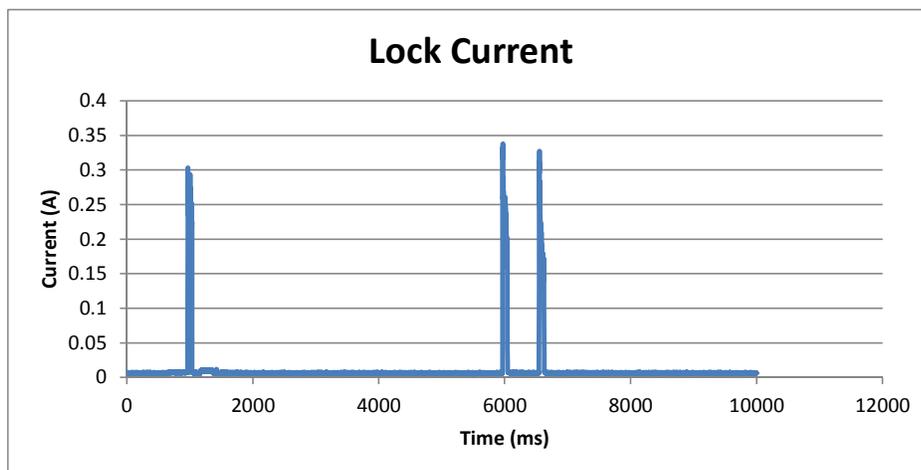


Figure 3. Battery output current waveform during unlock sequence

As shown in Figure 3, the unlock sequence consists of three pulses of current required by the lock mechanism. The initial pulse is the actual unlock pulse while the following two pulses are involved with resetting the lock mechanism. Closer analysis of this current waveform found that roughly 0.09 C of charge is required for the entire unlock sequence. Thus, for a battery voltage of 9V, the required lock energy is about 0.8J. Therefore, the energy harvester must capture about this much energy during one door open and close sequence in order to be viable.

Door Energy

Measurements of door parameters were made to determine approximate energy levels typically found in human powered door motion. Door opening and closing speeds were recorded for several users. A typical office door was weighed and measured such that its moment of inertia could be calculated.

Angular reference marks were placed on the floor beneath a typical office swing door at 15° intervals. A video was made while several volunteers opened and closed the door. The video data was reviewed frame-by-frame to extract the average time of motion for each user. The average time to open the door from fully closed to the 60° position was about 1.25s for an average speed of about 7.5 rpm. Figure 4 shows a still frame of the video for one user opening the door.



Figure 4. Still frame of door opening video trial

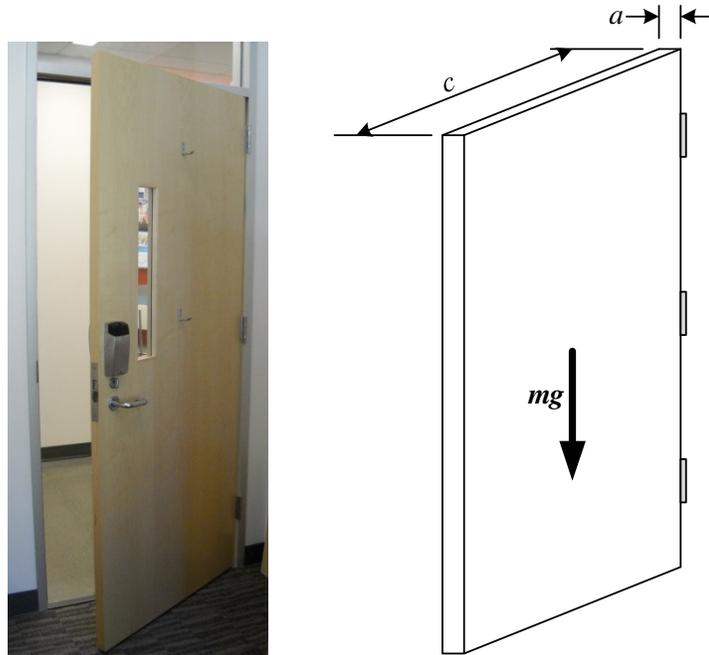


Figure 5. Photograph and diagram of typical office swing door

A human pushing on a door increases the rotational kinetic energy of the door. This energy is a result of the inertia of the door and its angular velocity. A typical office door is seen in the photograph displayed in Figure 5. The kinetic energy of the rotating door is calculated as follows:

$$KE = \frac{1}{2}I\omega^2$$

where I is the mass moment of inertia of the door with respect to its axis of rotation (axis of the door hinge) and ω is the angular velocity of the door in rad/s. The door is treated as a rectangular prism whose mass moment of inertia,

$$I = \frac{1}{3}m(a^2 + c^2)$$

where m is the mass of the door and a and c are its lateral dimensions as shown in Figure 5. The mass of the door used in the test was approximately 45 kg and the lateral dimensions a and c were 44 mm and 914mm respectively. During the door opening testing, the average door speed of 7.5 rpm resulted in the door's kinetic energy equal to approximately 3.9 Joules.

Laboratory testing of the generator found that about 1 ft·lb of torque was required to turn the generator shaft at 7.5 rpm with the nominal electrical load connected. The torque required to accelerate the door from a standstill to 7.5 rpm in 1s is about 7.27 ft·lb. The resulting additional force required to open the door measured at the door handle position is about 0.4 lb. The user would experience only about a 13% increase in effort required to open the door.

Generator Selection

Several small gear motors were investigated as candidates for the door energy harvesting generator unit. Catalog data for each motor was extracted and used for comparison. A simple DC motor model as shown in Figure 6 provided the necessary parameters needed for the comparison.⁷ Parameters typically available from catalog data include terminal voltage, V_t , no-load current, I_{NL} , no-load speed (in rpm), n_{NL} , stall current, I_{stall} , and/or armature resistance, R_a . These parameters can be combined to determine the motor constant, k , which provides the open-circuit output voltage as a function of shaft speed. The maximum output power for each motor could also be found from the maximum power transfer equation as shown below:

$$R_a = \frac{V_t}{I_{stall}} \quad E_{a_{NL}} = V_t - I_{NL}R_a \quad k = \frac{E_{a_{NL}}}{n_{NL}} \quad P_{out_{max}} = \frac{E_a^2}{4R_a}$$

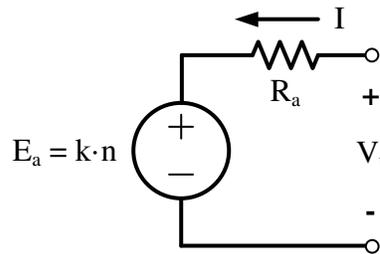


Figure 6. Simple DC motor model

Using these parameters together with a typical door opening speed of 7.5 rpm, the motors could be compared as shown in Table 1. From the comparison data for the available gear motors, the unit manufactured by Source Engineering was chosen for this application.⁸

Table 1. Gear motor parameter comparison

| Motor Manufacturer | V_t | I_{NL} | n_{NL} | I_{Stall} | R_a | k (V/rpm) | $P_{out-Max}$ |
|-----------------------|-------|----------|----------|-------------|---------------|----------------|---------------|
| Pittman | 19.1V | 0.08A | 82rpm | 1.5A | 12.7 Ω | 0.22 | 0.054W |
| Maxon | 36V | 6mA | 116rpm | 0.6A | 60 Ω | 0.31 | 0.022W |
| Buhler | 24V | 0.035A | 135rpm | 0.42A | 57 Ω | 0.16 | 6.5mW |
| Sayama | 12V | 0.02A | 62rpm | 0.41A | 29 Ω | 0.18 | 13mW |
| Source Engineering | 24V | 0.06A | 25rpm | 1.1A | 22 Ω | 0.91 | 0.53W |

Mechanical Design

The kinetic energy of the rotating door is transferred to a gear motor used as a generator mounted to the door at the point of the hinge. A photograph of the assembly was shown in Figure 2, and a CAD drawing of the motor with the motor shaft extending from it is seen in Figure 7. The motor housing firmly attached to the moving door rotates relative to its stationary shaft attached to the door hinge with a set screw as shown in Figure 2.

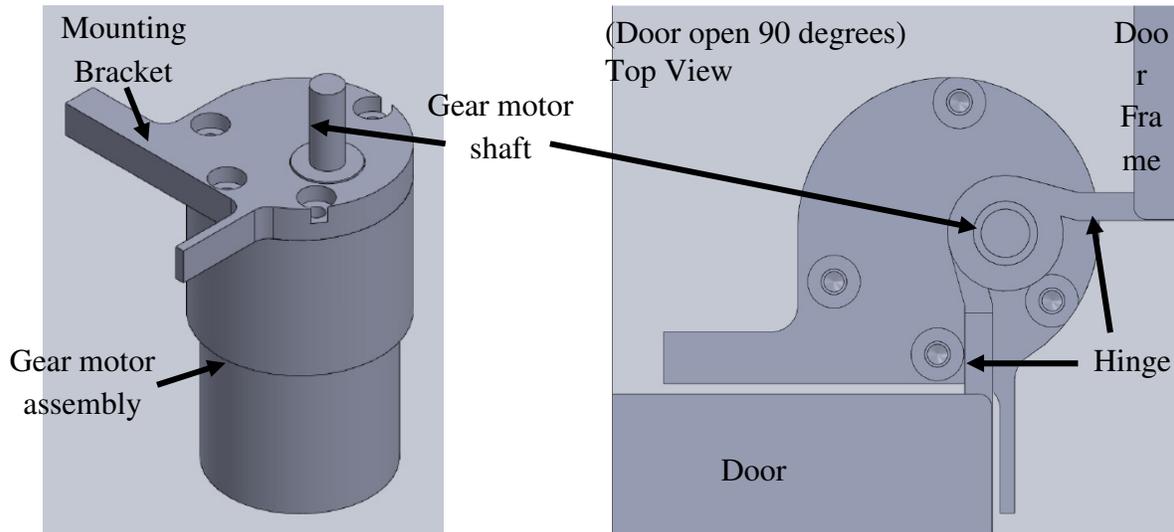


Figure 7. CAD drawings of generator mounting assembly

The unique design of the plate connecting the gear motor housing to the door provides a firm connection between them. In addition, it would be unnecessary to drill holes into the door, and therefore avoid damage to the door. Doors which swing in the opposite direction to that shown here can be accommodated by mounting the generator to the top of the hinge. As a result, it provides a more universal mounting configuration.

The mounting bracket was fabricated on a CNC machine using low-carbon 1018 cold-rolled steel to provide the necessary strength while keeping the thinnest possible profile. The bracket is secured to the generator using the standard tapped mounting holes on the motor housing. The design provides a snug fit against the door's inner surface and edge to capture door motion in both directions and convey that relative motion to the generator.

Electrical Design

The output voltage polarity of brush-type DC motors changes with the direction of rotation. Therefore, in order to capture energy in both directions of door motion, the output of the generator must be full-wave rectified. Schottky rectifiers were used to create the bridge circuit to minimize voltage drop. The generator output circuit is shown in Figure 8.

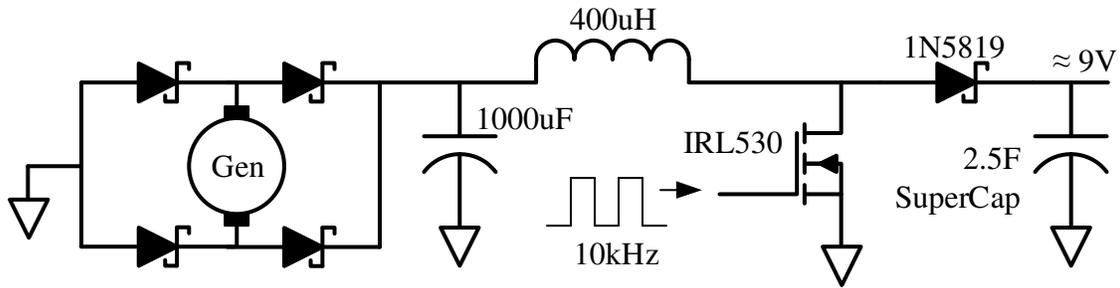


Figure 8. Generator output rectifier and boost converter schematic

As shown in Table 1, the motor constant for the chosen gear motor is 0.91 V/rpm. At a typical rotational speed of 7.5rpm, an open-circuit voltage of about 6.8V would be produced. The maximum power transfer would therefore occur when the generator output terminals were loaded to produce a voltage of about 3.4V. A boost converter would therefore be required to produce a voltage near the 9V required by the lock unit. A simple fixed frequency, fixed duty ratio boost converter was repurposed from another energy harvesting project. Figure 8 shows a schematic of the boost converter circuit. The MOSFET gate drive signal was obtained from a function generator for the experimental phase of the project. For the first cut design, a fixed frequency of 10 kHz was used. The duty ratio was adjusted to obtain maximum energy transfer for typical door opening speeds as discussed later. Due to the dynamic nature of the voltage source, a fixed duty ratio boost converter provides a solution that is a compromise but not the true optimum performance.

Because of the short duration of the generator output pulse during door opening and closing operations, the energy could not efficiently be captured by an electrochemical process. Therefore, high capacity capacitors (referred to as super capacitors or ultra-capacitors) were investigated as a means of storing the pulsed energy.⁹ Based on the available supercapacitor capacitance, voltage rating values and an acceptable voltage sag during the lock current pulses, a bank of four 10F supercapacitors configured in series was chosen.¹⁰ The total energy storage capacitance was therefore 2.5F. Each supercapacitor is rated at 2.7V. A passive balancing resistance of 1M Ω was placed in parallel with each supercapacitor to help maintain voltage sharing while minimizing leakage current.

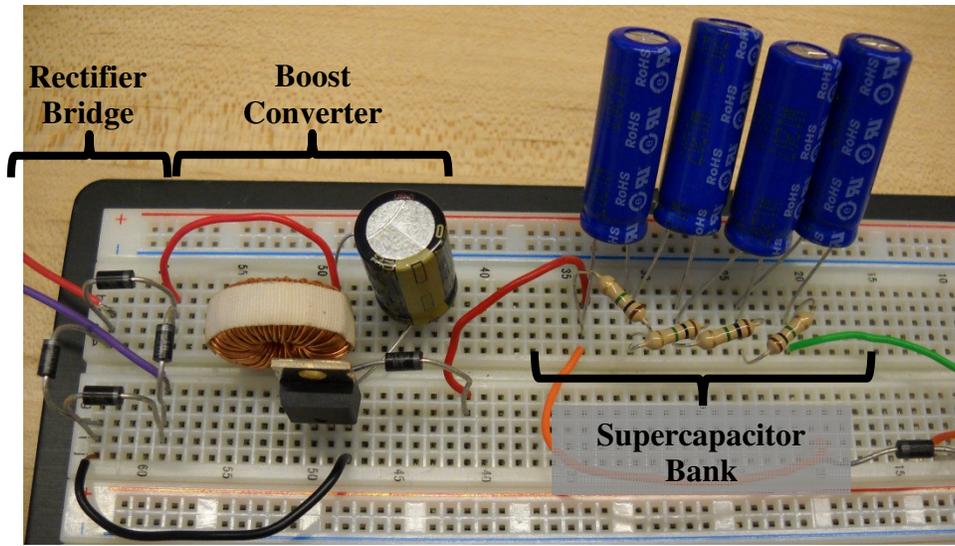


Figure 9. Photograph of rectifier bridge, boost converter and supercapacitor bank breadboard circuit

Test Data

The battery pack of the lock was removed and replaced with the 2.5F supercapacitor bank that had been pre-charged to 9.0V with an external power supply. An unlock sequence was initiated by a card swipe while the capacitor bank voltage was measured with a 5 ½ digit DMM. The capacitor bank voltage was observed to decrease by about 35mV as a result of the unlock operation. This voltage sag is consistent with an average current draw of about 16mA for the duration of the unlock sequence time of about 5.5 seconds.

The energy harvesting generator was mounted to a door as shown previously in Figure 2. The open circuit output voltage of the generator, after rectification, was recorded during several trials of opening and closing the door. Figure 10 shows the typical open-circuit voltage waveform. The waveform roughly approximates a half sine wave with a peak of about 10 V and duration of about 2s.

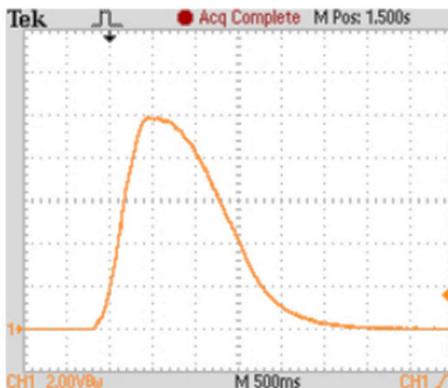


Figure 10. Open circuit generator output voltage waveform

The generator/rectifier circuit was then connected to the input of the boost converter. The output of the boost converter was connected to the supercapacitor bank that was pre-charged to 9.0V with an external power supply. Many door opening and closing trials were conducted for various values of boost converter duty cycle. The change in the supercapacitor bank voltage was measured for each trial. A duty ratio of 35% was found to produce the maximum change in capacitor bank voltage of about 50mV for one complete open and close cycle of the door.

Figure 11 shows the generator output voltage (boost converter input voltage) and boost converter output current (supercapacitor bank input charging current) for a typical door operation in one direction. For a fixed duty ratio of 35% and a fairly stiff output voltage of 9V, the boost converter remains in discontinuous conduction mode until the input voltage reaches about 5V. A further increase of the input voltage results in continuous conduction mode which tends to clamp the input voltage. As mentioned earlier, this type of operation does not provide maximum power transfer from high impedance sources such as the generator used here. Closed loop control would need to be implemented to resolve this issue.

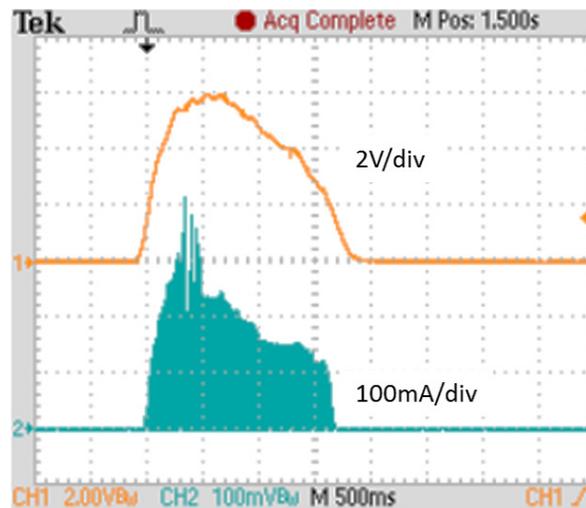


Figure 11. Generator output voltage and boost converter output current waveforms.

Conclusions

A practical system for harvesting the energy produced by human door openings was presented. The goal of capturing enough energy during one door open and close cycle to replace that used by the unlocking mechanism was demonstrated. A simple DC generator with a non-intrusive hinge mounting system provides the means for converting the energy of the swinging door into electrical energy. The amount of energy captured is sufficient to sustain the system yet the burden placed on the door user is minimal.

The work presented here represents a proof of concept. Many of the practical problems of this method were resolved while there are still some that will require future work before the system could be deployed for general use. The supercapacitors must be protected from

charging beyond their working voltage rating. A mechanism to control self-discharge of the supercapacitors during long periods of door inactivity must also be implemented. More optimal energy extraction could be achieved by employing smarter voltage and/or door speed sensing into the DC-DC converter control loop.

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