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# A Low-Power Instrumentation and Recording System for Swing Door Usage Analysis

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## Abstract

As part of an energy harvesting investigation, a custom monitoring device was designed, constructed and implemented to measure and record the characteristics of human-operated swing door usage in a typical public building setting. The device was designed to be portable, battery-powered, easily installed without damaging the door, inconspicuous, and non-interfering with normal door operation. The dynamic position of the door is measured and stored in on-board non-volatile memory that is later uploaded for analysis. A real-time clock is used to timestamp each door opening event. The system is easily calibrated when installed on the door. In this paper, the electrical, mechanical, and software designs are presented and discussed. System calibration and resolution is also presented. Data formatting and analysis is described and experimental results from the system are presented.

## Motivation and Introduction

Energy harvesting (which here may also be called *energy scavenging*) is the process of capturing forms of energy that might otherwise be neglected or wasted for the purpose of powering electronic systems such as environmental monitors or other remotely located, mobile and/or wireless systems [1-3]. This type of energy capturing is particularly useful in systems where the power demand or duty ratio is small. Investigations into capturing the energy generated by humans have been presented [4]. Systems which harvest wasted energy expended while walking, have been extensively investigated [5,6].

The energy source being studied here is that of humans pushing or pulling open the doors (swing doors) of public buildings. The doors studied are those that are typically found in hallways or building entrances. The doors have a closure mechanism that provides the spring force to close the door as well as some level of damping to limit the opening and closing velocities for safety and to prevent the door from slamming shut. The static and dynamic characteristics of the door under test have been previously identified [7]. These characteristics are then used together with the long-term monitor data to quantify the energy potential.

In public buildings, the doors can be opened several hundred times each day, thus the potential exists for a significant amount of energy being expended by humans. There are many possible uses for the energy harvested from human powered mechanisms such as doors. Measurement of the door usage characteristics in its natural (non-laboratory) environment is the focus of the system presented here. This information can then later be used to evaluate the human energy potential of the door operation.

By using low-power electronic devices and smart power management, a portable battery-operated system to measure the door usage characteristics and patterns can be realized. Custom portable monitoring systems have been used in biomedical applications [8,9]. The hardware and software design considerations for the unique application of monitoring swing door usage are presented and discussed here.

## System Design Goals

Although swing doors have a wide range of hinge and closure mechanisms, the instrumentation concepts remain the same. To properly assess the true energy potential of human-operated swing doors, the motion of the door must be monitored over an extended period of time and in a non-intrusive manner. That is, the monitor hardware must not interfere with the operation of the door and must not be so noticeable as to make users avoid opening the door.

Mechanically, the monitor design goals are as follows:

- Easily mounted and removed from door frame or hinge without damage to the structure.
- Small enough to be unobvious to door users.
- Durable enough for prolonged use (indoor only)
- Position sensing arm shall be self-returning and not interfere with normal door operation.
- External serial port connector for easy data access.

Electrically, the monitor design goals are as follows:

- Battery powered
- Low power consumption
- Position resolution of 5 degrees or better
- Sample fast enough to provide dynamic position accuracy of 5 degrees or better.
- Enough memory to store at least one day’s worth of data.
- Timestamp door activity
- Serial port for data upload to computer
- Easy calibration.
- Adjustable start/stop threshold position.

Another design criterion is the ability to sense when the door has been propped open and to stop acquiring data during this condition. Also, the system must not overwrite stored data in the event that the memory becomes full. These requirements are handled in the software of the onboard microcontroller processor and will be discussed later.

**Methods and Materials**
**Hardware**

Figure 1 shows the assembly drawing of the door monitor system. The project box contains the circuit board and batteries (3 - AAA size) to power the system. In practice, the project box enclosure is rigidly mounted to the doorframe of the door under test, typically on the hinge hardware, with the fixed and movable clamping bars. Figure 2 shows a photograph of the device mounted to the protruding door hinge hardware with the clamping bars secured with machine screws. Both right hand and left hand swinging doors can be accommodated.

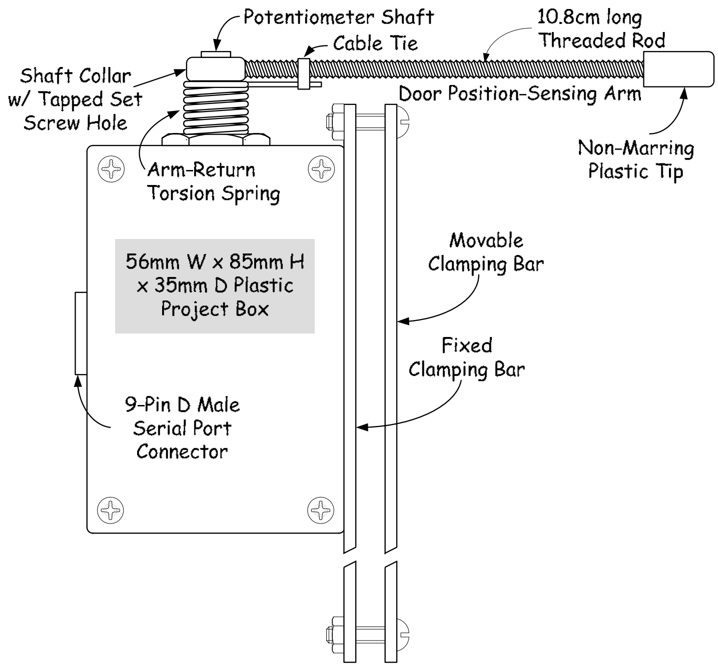
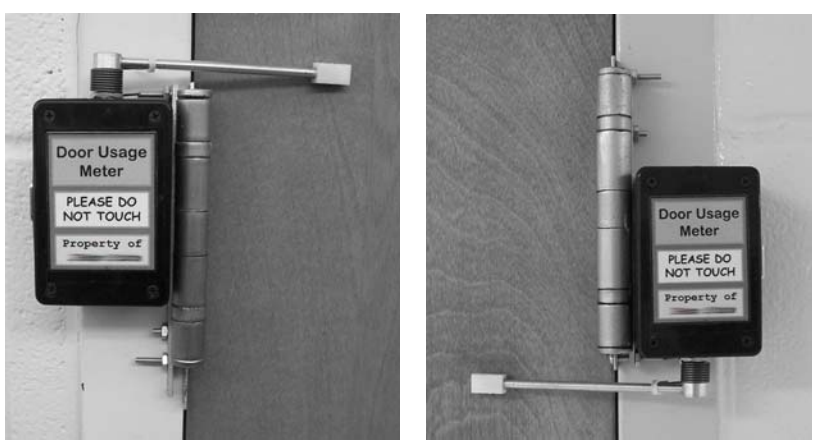



Figure. 1. Door monitor assembly drawing.




(a) (b)

Figure. 2. Door monitor system installation on (a) right-hand and (b) left-hand swinging doors.

The shaft of the door position-sensing potentiometer extends out of the top of the enclosure. The sensing arm (threaded rod) is attached using a simple tapped collar as shown in Figure 1. A small torsion spring is used to return the sensing arm and keep it in contact with the swinging door surface. A plastic tip is mounted to the end of the threaded rod to produce a non-marring, low-friction contact area.

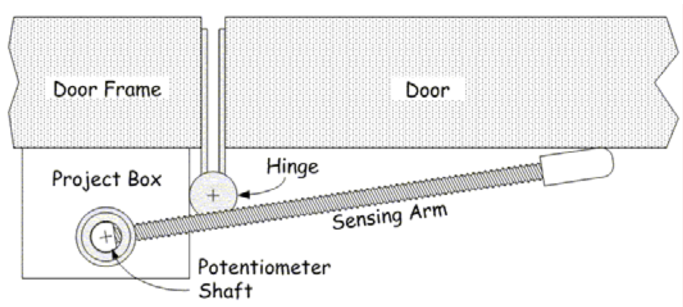



Figure 3. Sensing arm and door position diagram, top view.

The required length of the position-sensing arm is primarily determined by the desired angular position resolution. Figure 3 shows a top view of the door monitor position-sensing components and door hinging configuration. The center of rotation of the potentiometer shaft is not coaxial with the center of rotation for the door. Therefore, the length of the sensing arm is an integral part of the angular position resolution.

Because the potentiometer shaft is off-axis with the door rotation axis, its rotation is not linearly related to door rotation. The relationship is however predictable and through careful design and calibration, the door position can be measured accurately without the need for the aligning these axes. This keeps the system flexible for use on many types of door/hinge arrangements.

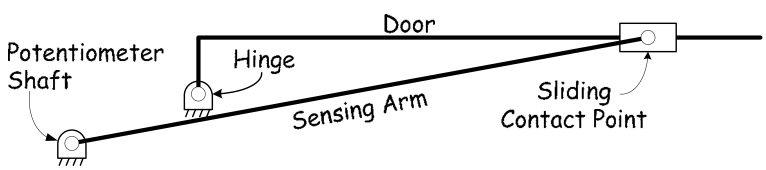



Figure 4. Linkage model of sensing arm and door.

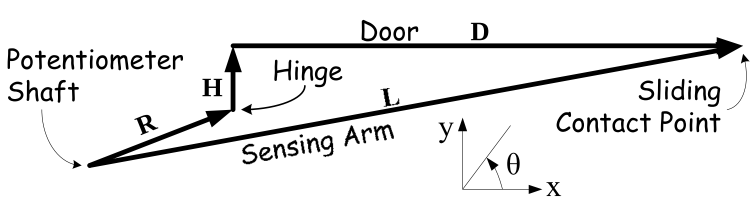



Figure 5. Vector model of sensing arm and door.

The sensing arm arrangement in Figure 3 can be modeled as a linkage system as shown in Figure 4 where the system is shown in its initial position, that is when the door is closed. Figure 5 consists of a vector diagram specifying the positions of the components of the door/potentiometer linkage system given in Figure 4. The vectors are defined as follows:

**R** = the position of the door hinge with respect to the potentiometer shaft.
**H**+**D** = the position of the contact point on the door surface with respect to the door hinge.
**L** = the position of the sliding contact point with respect to the potentiometer shaft.

The following vector equation relates the positions of the system components as given in Figure 5.

$$\mathbf{R} + \mathbf{H} + \mathbf{D} = \mathbf{L} \tag{1}$$

By resolving the vectors in (1) into their rectangular or x and y components, the following scalar equations can be written as (2). The angles for each of the components positions given in (2) are measured from the horizontal in a counter-clockwise direction.

$$\begin{aligned} R\cos\theta_R + H\cos\theta_H + D\cos\theta_D &= L\cos\theta_L \\ R\sin\theta_R + H\sin\theta_H + D\sin\theta_D &= L\sin\theta_L \end{aligned} \tag{2}$$

Several of the parameters of (2) are known or are related by constants. The positions of the potentiometer axis and door hinge axis are fixed at installation, therefore **R** is known. The distance of the hinge axis from the door surface is also fixed, thus the distance $|\mathbf{H}| = H$ is also known. The hinge plate angle, $\theta_H$, always forms a right angle with the door angle, $\theta_D$, such that $\theta_H = \theta_D + 90°$. Using the trigonometric identities, $\cos(\theta + 90°) = -\sin\theta$ and $\sin(\theta + 90°) = \cos\theta$, (2) can now be written as,

$$\begin{aligned} R_x - H\sin\theta_D + D\cos\theta_D &= L\cos\theta_L \\ R_y + H\cos\theta_D + D\sin\theta_D &= L\sin\theta_L \end{aligned} \tag{3}$$

The unknowns in (3) are now D, $\theta_D$ and $\theta_L$. The desired relationship is the angle of the sensing arm, $\theta_L$ as a function of the angle of the door, $\theta_D$. By solving each of the component equations for D and setting them equal to each other, a transcendental equation in the desired variables results:

$$\left[L\cos\theta_L - R_x + H\sin\theta_D\right]\sin\theta_D = \left[L\sin\theta_L - R_y - H\cos\theta_D\right]\cos\theta_D \tag{4}$$

With the system constructed as shown in Figure 1 and mounted as shown in Figure 2, the known dimensional values are Rx = 3.97cm, Ry = 0.317cm and H = 1.75cm. Using these values, (4) can be numerically solved for $\theta_L$ as a function of $\theta_D$ for various sensing arm lengths, L. Figure 6 shows a plot of these functions.

To determine the resolution of the overall door angle measurement, the static sensitivity of the sensing arm angle, $\theta_L$, to door angle, $\theta_D$, is required. This can again be numerically determined from the functions plotted in Figure 6. Figure 7 shows the plots of $\partial\theta_L/\partial\theta_D$ for various sensing arm lengths, L. For very long arm lengths, the static sensitivity is nearly unity as expected. As the arm length becomes short, the sensitivity varies greatly from less than one to greater than one over the swing arc of the door. If the arm were made too short it would actually lose contact with the door at some angle. For the configuration used here, this loss of contact occurs for sensing arm lengths less than about 6.9cm.

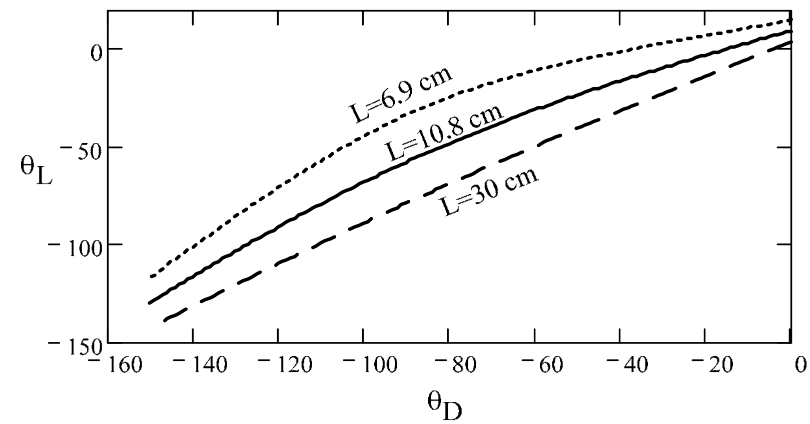



Figure 6. $\theta_L$ versus $\theta_D$ for various arm lengths, L.

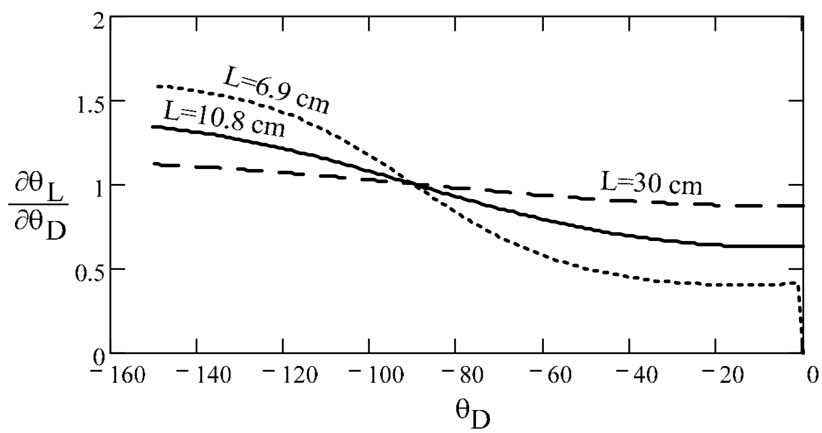



Figure 7. $\theta_L$ sensitivity versus $\theta_D$ for various arm lengths, L.

The transfer function of the potentiometer can be determined using the effective electrical angle of the device. The effective electrical angle of a potentiometer is the angle over which the wiper voltage changes as the shaft is rotated. This angle is usually less than the full range mechanical angle. For the door position sensing potentiometer used here (Bourns part number 81A1AB28B25), the effective electrical angle is 240° while the mechanical range of rotation is 300°. The transfer function is ratiometric with the supply voltage, $V_S$. The potentiometer wiper voltage, $V_w$, with respect to circuit ground increases from 0V when $\varphi_E=0$ to $V_S$ when $\varphi_E=240°$. The resulting transfer function is then,

$$\frac{V_W}{\varphi_{E\max}} = \frac{V_S}{240°} \quad \text{Volts}/° \tag{5}$$

The potentiometer voltage is measured with an eight bit analog to digital converter. The reference voltage for the A/D is also the potentiometer excitation voltage, $V_S$, therefore the measurement is insensitive to changes in this voltage. The resolution for the combined potentiometer and A/D converter is then

$$\text{Resolution} = \frac{V_S}{2^8}\frac{240°}{V_S} = 0.94°/\text{bit} \tag{6}$$

The overall resolution of the sensing system can now be estimated by combing the resolution of the potentiometer and A/D converter from (6) with the sensitivity of the sensing arm shown in Figure 7. From Figure 7, the minimum resolution occurs with the shortest sensing arm length and for door angles near zero degrees. Here the sensitivity is approximately 0.4 °/° which results in an overall resolution of 2.34°/bit. The design goal was a resolution of 5°/bit and therefore an arm length of 6.9cm would be adequate for the mounting configuration presented. In the application to ensure that the sensing arm remained in contact with the door for several mounting configurations, the slightly longer length of 10.8cm was used. This length resulted in an estimated resolution of 1.51°/bit.

The door monitor system need only be active during the time when the door is not in the closed position. Therefore, the system can be placed into a low power sleep mode between door opening events to conserve battery energy. The sleep mode power is primarily that of the system microcontroller. The door position sensing potentiometer wiper voltage level is used to awake (and sleep) the system.

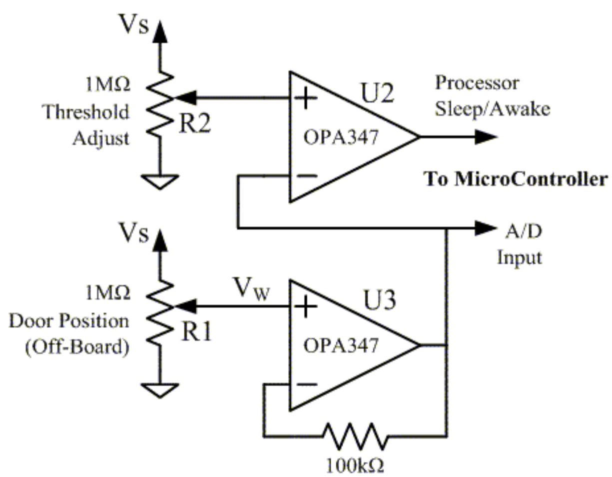



Figure 8. Buffer and comparator circuit schematic.

Figure 8 shows the schematic diagram of the door position potentiometer sensing circuit. R1 is the potentiometer that is connected to the door position sensing arm. A large resistance value is required for the potentiometer since it is always connected to the battery regardless of the mode of operation and therefore always consumes energy. A micro-power operational amplifier (U3, OPA347) is then used to buffer the R1 wiper voltage to reduce the source resistance presented to the microcontroller A/D input.

The output of U3 is also sensed by the comparator formed with another micro-power op amp (U2) to create a Sleep/Wakeup signal for the microcontroller which is ultimately determined by the door position. The Sleep/Awake threshold is set by adjusting the trimmer potentiometer, R2, when the system is installed on the door. The quiescent supply current for U2 and U3 is typically 34μA each [10].

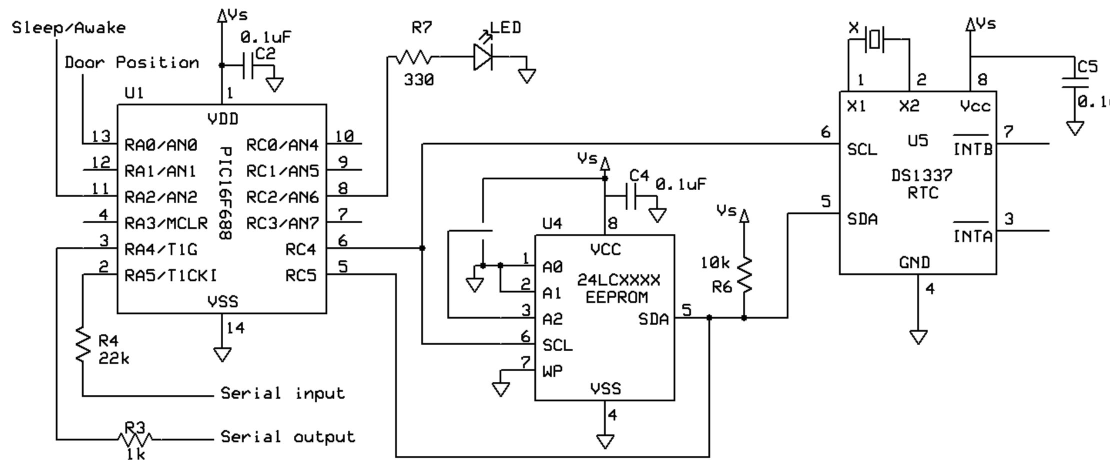



Figure 9. Microcontroller, EEPROM and real-time clock circuit schematic.

When the microcontroller is awake, the microcontroller's A/D converter samples the output of U3 at a rate of 16 samples per second. This sampling rate is a compromise between dynamic resolution and system data storage memory capacity.

The use of several public building doors was observed to obtain an estimate of door opening and closing times. Typically, the doors were pushed or pulled to an open position of roughly 90° in about 2 seconds. The full cycle of door opening by the user and closing by the automatic closer mechanism took approximately 5 seconds.

An average door opening rate of 90°/2s requires a minimum sampling rate of 9 samples per second to achieve a dynamic resolution of 5°/bit. However, the sensitivity of the potentiometer angle to door angle must also be included. When the minimum sensitivity of 0.62 °/° for a 10.8cm sensing arm is included, the minimum sampling rate required to achieve a dynamic resolution of 5°/bit is 14.5 samples per second. Thus a slightly higher sampling rate of 16 samples per second is implemented in the system.

At a sampling rate of 16 samples per second, a typical door opening and closing event takes 80 samples. Using an 8-bit A/D converter, one byte of memory is required for each sample and therefore 80 bytes are needed for each event. Door use observations also determined that roughly 500 opening and closing events occurred each day thus requiring approximately 40k bytes of memory capacity. This capacity is obtained by using one 512kbit (64k x 8bit) EEPROM memory device; the 24LC512 manufactured by Microchip

Technology, Inc. This device consumes very little power, has a wide operating voltage range and uses an $I^2C$ serial interface for data transfer which is easily implemented with a microcontroller [11].

Figure 9 shows the electrical schematic for the microcontroller, data storage memory (EEPROM) and real-time clock (RTC) circuit of the door monitor system. The RTC, DS1337 manufactured by Maxim Integrated Products, communicates with the microcontroller via the same $I^2C$ serial bus used by the EEPROM and has a typical quiescent supply current of 500nA at 4.8V [12]. The RTC is used to provide a data/time stamp for each door opening event.

The PIC16F688 microcontroller manufactured by Microchip Technology, Inc. is used as the controlling processor for the system. This microcontroller contains a multiplexed A/D converter which is software configurable for up to 10-bits of resolution (only 8-bits are used here). The PIC16F688 consumes very little supply current during operation (typically 0.8mA at 5V), has a very low sleep current level (nominally 3nA at 5V), and has a wide operating voltage range (2V – 5.5V), all of which make it ideal for battery operated equipment [13].

The estimated power budget for the system based on manufacturer supplied data is shown in Table I for both sleep mode and active mode. On the prototype unit at 4.6VDC, the sleep mode current was measured to be 42µADC and the active current was 670µADC.

The power budget numbers are used to determine the battery size and expected lifetime. To satisfy the voltage requirements of the devices with a comfortable margin for battery droop, three alkaline cells are used. This arrangement produces a nominal voltage of 4.5VDC. To avoid special purpose batteries, only readily available standard cells are considered (AAA, AA, C, etc.).

TABLE I. System Power Budget

| Device | Sleep (µA) | Active (µA) |
|---|---|---|
| MicroController (4MHz) | 0.003 | 800 |
| EEPROM | 1.0 | 50* |
| Real-Time Clock | 0.5 | 150 |
| Op-Amps (Total for 2 devices) | 68 | 68 |
| Potentiometers (Total) | 10 | 10 |
| Totals | 79.5 | 1078 |

* 5mA write current at 1% duty ratio

The charge required for one day of operation with 500 door openings can be estimated as shown in (7) using the quiescent current values shown in Table I.

$$
\begin{aligned}
Q_{Active} &= \left(\frac{500\ \text{openings}}{\text{day}}\right)\left(\frac{5\ \text{s}}{\text{opening}}\right)\left(\frac{1\ \text{h}}{3600\ \text{s}}\right)1.078\text{mA} \\
&= 0.75\text{mAh / day} \\
Q_{Sleep} &= \left\{24\text{h} - \left[\left(\frac{500\ \text{openings}}{\text{day}}\right)\left(\frac{5\ \text{s}}{\text{opening}}\right)\left(\frac{1\ \text{h}}{3600\ \text{s}}\right)\right]\right\}0.0795\text{mA} \\
&= 1.85\text{mAh / day} \\
Q_{Total} &= 2.6\text{mAh / day}
\end{aligned}
\tag{7}
$$

An alkaline (zinc / manganese dioxide) AAA size cell has a nominal charge capacity of 1250mAh for small discharge rates [14]. The system could therefore be powered for approximately 480 days using AAA cells. Three AAA cells connected in series to produce a nominal voltage of 4.5V are used in the door usage measurement system.

**Software**

The microcontroller software is written using PICBASIC but could be performed in any suitable programming language. Many features have been designed into the software for system calibration, housekeeping (setting RTC, etc.), and downloading of stored data.

The microcontroller starting state is in the sleep mode (low-power standby). In this mode, the system consumes the least battery power. When the door is opened slightly such that the potentiometer wiper voltage, $V_W$, exceeds the threshold voltage, the microcontroller wakes up and begins executing the active routine.

Once awake, the microcontroller immediately reads the current date and time from the RTC and stores this information in EEPROM. The date and time data is read from the RTC registers as seven 8-bit bytes in binary coded decimal format [12]. These seven bytes plus a trailing eighth byte set to a value of 255 are written to the EEPROM. The 255-value byte is used as a delimiter to tag each door opening event in memory.

After the RTC data and delimiter values are stored, the microcontroller begins to sample the door position potentiometer voltage at a 16 Hz rate. The voltage is measured using 8-bits of A/D resolution therefore one byte per sample is stored. After each voltage sample, the status of the door is checked to see if the door is still open. If the door is closed, the microcontroller returns to the sleep state.

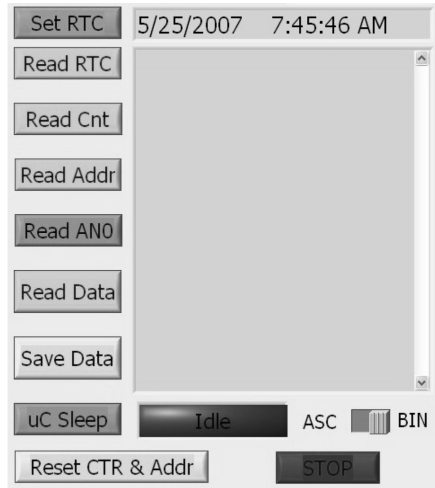



Figure 10. GUI for handheld PC.

The measurement system communicates with an external computer via an RS232 serial port. The system responds to serial commands to perform various housekeeping tasks. These tasks include reading the EEPROM data, synchronizing the RTC with the clock of the external computer, and resetting the memory counter to prepare for taking more data. Figure 10 shows the graphical user interface (GUI) of the external computer (handheld) application used to communicate with the measurement system.

The stored data is transmitted to the external PC via the serial port at 9600 baud in 8N1 format. Each byte of data is sent as an ASCII character which is then decoded by the external PC software. The ASCII decimal 255 character that was formatted into the last byte of the date/time stamp string serves as the marker to denote the start of each door opening event's data.

## System Calibration

The door usage measurement system is calibrated after installation on the door under test. A template is placed on the floor over which the door swings. The template is essentially a large protractor and contains radial lines in 5 degree increments with the origin located directly beneath the door hinge. The measurement system is placed in its normal mode of operation while the door is manually moved through its full range of swing stopping at each 5 degree mark for a few seconds. The stored data is then downloaded and analyzed to create a table to map the door potentiometer voltage to the position of the door. Voltages between the table values can then linearly interpolated. Table II contains typical calibration data for door positions from -15° (wakeup threshold) to -135° (door stop) in 5° steps.

TABLE II. Calibration lookup table data.

| Door Angle (°) | Digital Value | Door Angle (°) | Digital Value |
|---|---|---|---|
| -15 | 42 | -80 | 93 |
| -20 | 46 | -85 | 98 |
| -25 | 50 | -90 | 104 |
| -30 | 53 | -95 | 109 |
| -35 | 57 | -100 | 114 |
| -40 | 60 | -105 | 120 |
| -45 | 64 | -110 | 126 |
| -50 | 68 | -115 | 133 |
| -55 | 72 | -120 | 139 |
| -60 | 76 | -125 | 145 |
| -65 | 80 | -130 | 151 |
| -70 | 84 | -135 | 158 |
| -75 | 89 | | |

## Example Results

The calibration data of Table II was used together with the spatial orientation of the door position sensing potentiometer, R1, to determine the actual sensing arm angle, $\theta_L$, as a function of door angle, $\theta_D$. These measured values are plotted together with the predicted values (the curve for L=10.8cm shown earlier in Figure 6) in Figure 11. The actual values correspond very well with those predicted by (4). Much of the variation in the measured values is due to the quantization error of the A/D converter.

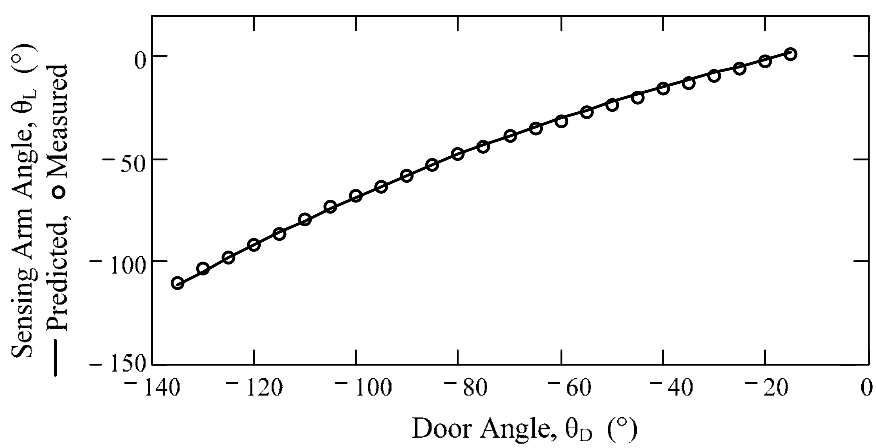



Figure 11. Predicted and measured sensing arm angle as a function of door angle for L=10.8cm.

The door monitor system was mounted to a hallway swing door in a college classroom building as shown in Figure 2. Door usage data was recorded over a period of one week. The recorded data was uploaded to the handheld PC each day. Figure 12 shows a plot of the recorded data for two typical consecutive door opening events. From the recorded data, the door position at any given point can be determined by using the calibration data in Table II.

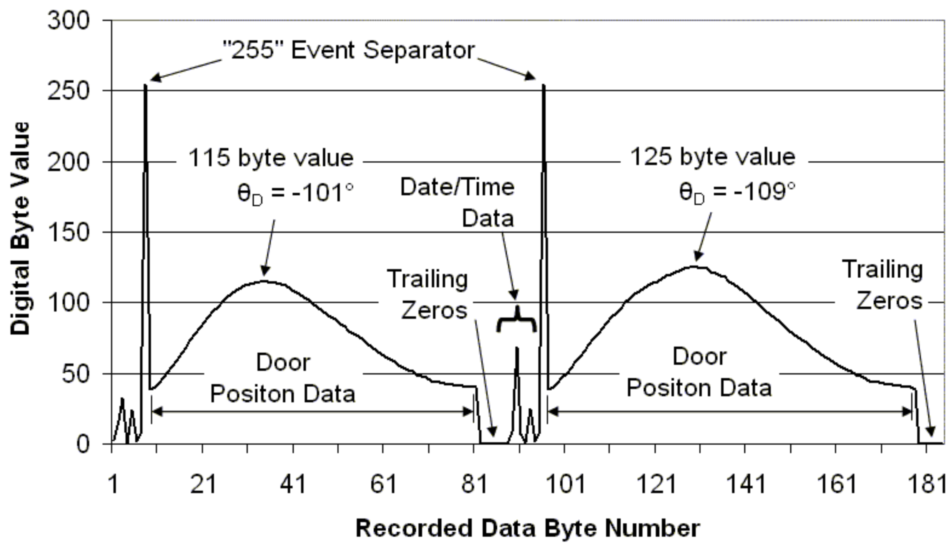


Figure 12. Plot of recorded door usage data for two consecutive door opening events.

From Figure 12 it can be seen that the door was opened to positions of -101° and -109° on the two consecutive openings. In each opening, the user pushed or pulled the door to its respective maximum position in 1.6s and 2.0s. The door closer mechanism returned the door to the closed position with a damped, tapered velocity motion to prevent slamming.

The date/timestamp information for each door opening event is also useful in energy harvesting applications. Figure 13 shows a histogram for door openings over a typical 24 hour period. This data shows the hours over which the majority of the energy is produced by the users. Such data is also useful for other applications such as maintenance and room/building use scheduling and planning.

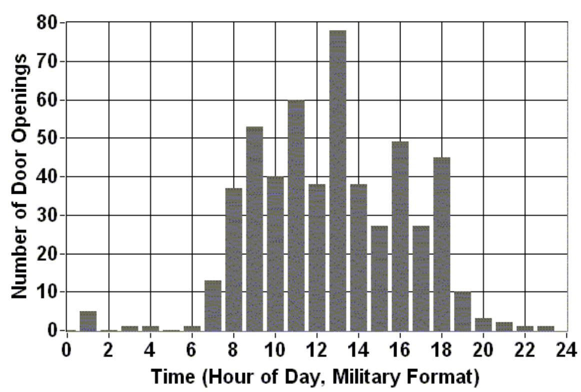


Figure 13. Histogram of door opening events for one day.

## 5. Conclusion

A low-power system for measuring and recording the usage of a swing door was designed, constructed, calibrated, and implemented. The system electrical and mechanical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design goals were achieved through careful analysis and software design as presented and discussed. The design is simple, effective and flexible, yet meets the stringent performance requirements. System installation and calibration can easily be performed on many door hinge arrangements. The door monitor system, together with the door/closer mechanism characterization data, allows the stored energy at any door position to be determined. This stored energy, which is generated by human users, can then be quantified without special loading or testing of the human subjects.

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**Biographies**

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Thomas H. Gavigan is an Assistant Professor at Penn State, Berks Campus in Reading, PA. He received his B.S. in Mechanical Engineering from Drexel University in 1970 and his M.S. in Engineering Mechanics from Penn State in 1977. Mr. Gavigan teaches in the areas of Engineering Mechanics and Engineering Design.