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Analog Microcontroller Model for an Energy Harvesting Round Counter

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ABSTRACT
An energy harvesting electronic round counter has been developed that uses piezoelectric transducers mounted on the gun to generate electrical energy in response to the strain associated with each fired round. These transducers produce limited energy, so lumped-parameter models of the transducer and round counter circuitry were developed to optimize the electrical efficiency. The greatest energy requirement of the circuitry is associated with a microcontroller that updates the cumulative count in non-volatile memory. An analog model of the current-voltage relationship for the microcontroller was developed using timed stages to represent sequential execution of the firmware. Simulation results were compared to experimental data and used to optimize the circuit design and configuration of the piezoelectric transducers.

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INTRODUCTION

An accurate count of the number of rounds fired is critical for evaluating the age of a gun tube with respect to its safe service life. Currently, the firing history of each gun is manually recorded on a Weapon Record Data Card that must be accurately maintained throughout the weapon's life. If a card is missing or incomplete, critical information on the safe service life of the gun tube is permanently lost. An electronic round counter has been designed that maintains a history of the rounds fired to supplement the Weapon Record Data Cards [1].

The round counter uses piezoelectric transducers mounted on the gun to generate electrical energy in response to the strain associated with each fired round. Piezoelectric materials become electrically polarized in proportion to an applied mechanical strain [2] resulting in a conversion between mechanical and electrical energy. A portion of this energy is used by the electronics to update a count in the non-volatile memory of a microcontroller. No batteries or other external power source are required. This eliminates the logistic burden associated with battery replacement and disposal for fielded electronics in accordance with requirements from the Army Capstone Concept [3]. In addition, the electronics can be permanently sealed to minimize the effect of the severe environmental conditions under which the system is expected to operate.

MODELS

Piezoelectric Transducer

Figure 1 shows the model used to represent a piezoelectric transducer [3], where V_{OC} is the open circuit piezoelectric voltage generated by the strain and C_f is the film capacitance. This model was used in determining the film capacitance required to generate sufficient energy to complete a successful update of the cumulative round count to non-volatile memory. This capacitance was then used in defining the configuration of the piezoelectric transducers. A minimum operating value of C_f was desired due to the limited surface area available for mounting piezos on the gun system.

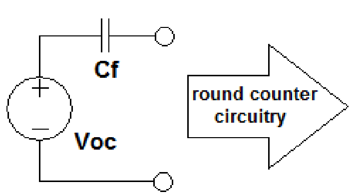

Figure 1. Equivalent circuit model for a piezoelectric transducer

Microcontroller

The greatest energy requirements of the round counter circuitry are associated with the Microchip PIC12LF1822 microcontroller [4]. An analog model of the current-voltage relationship for the microcontroller was developed to accurately simulate the time varying power requirements.

Figure 2 shows the logic used to represent activation of the microcontroller. An S-R flip-flop is used to define the on state of the microcontroller as $Q = 1$ ($Q_{bar} = 0$) when the supply voltage, V_{dd}, is greater than a threshold voltage, V_t. The processor resets, $Q = 0$ ($Q_{bar} = 1$), if V_{dd} falls below the brown-out voltage, V_{BOV}. V_{BOV} is given in the datasheet and was verified experimentally. In our tests $V_t = V_{BOV}$. A brown-out reset (BOR) prevents corruption of memory which may occur when the chip loses power during operation. A switch and an RC circuit are used to delay the BOR for approximately 100 μs in order to help prevent oscillations of the S-R flip flop at voltages approaching V_{BOV}.

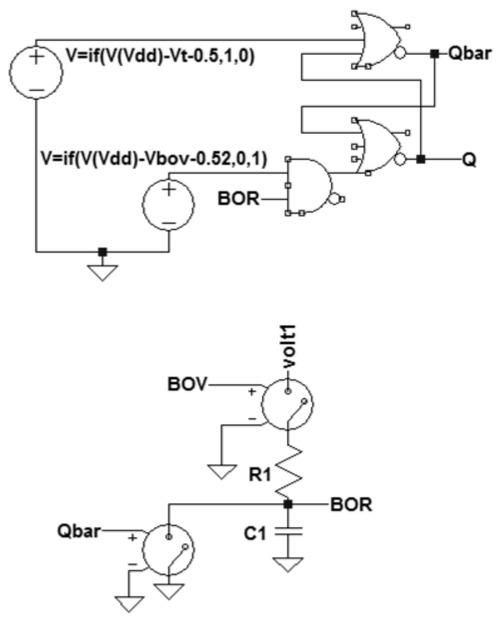

Figure 2. Microcontroller on state and BOR logic circuitry

Microcontroller current-voltage (I-V) characteristics cannot be derived directly from the manufacturer data sheet because they are a strong function of the resources used by the firmware. There are five separate sections of code in our firmware sequence: startup, analog to digital conversion, determining a memory address, updating non-volatile memory, and system sleep. Each section uses different microcontroller resources and therefore has a unique I-V relationship. A series of tests were conducted to establish these relationships. Microcontroller current was measured at a variety of supply voltages in the range of interest while performing a sequence of operations. Figure 3 shows a typical result of the I-V measurements. For each section of code, current is a linear function of the voltage with a nonzero intercept. Two separate linear stages were used to represent the startup condition to help prevent oscillations associated with a brown-out condition.

The resulting circuit model for the linear I-V relationships is parallel combination of six stages, each of which is comprised of a series combination of a resistor, DC voltage source, and voltage controlled switch. The resistor value is proportional to the slope of the I-V curve and the DC voltage source corresponds to the intercept. The switch is active for the length of time the section of code is executing.

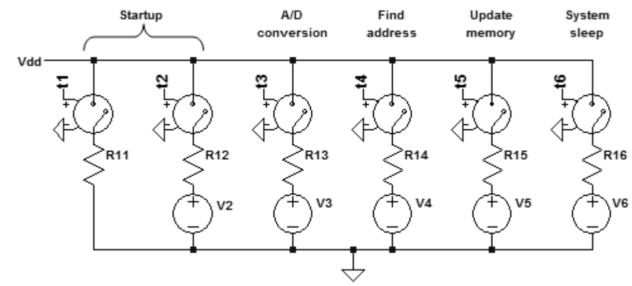

Figure 4 shows the six-stage linear circuitry corresponding to each section of code. The first two stages represent chip startup, and the next four stages correspond to A/D conversion, finding an address in memory, updating memory, and system sleep.

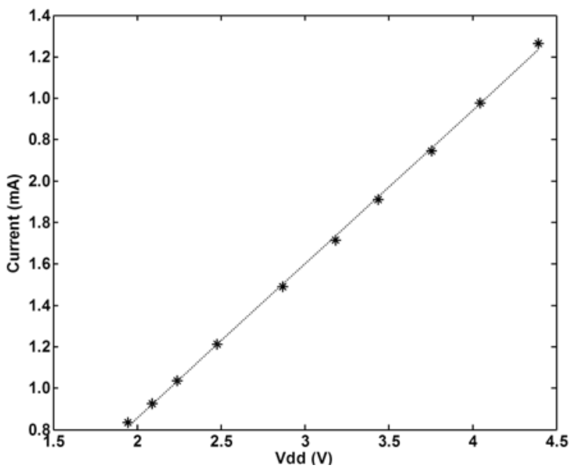

Figure 3. Typical I-V characteristic for the PIC12LF1822: Current vs. supply voltage while finding a memory address (16 MHz clock speed)

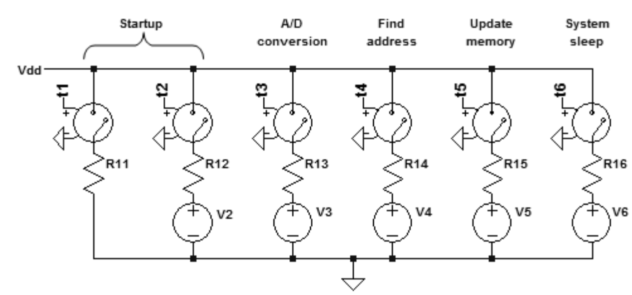

Figure 4. Implementation of I-V characteristics for each firmware function

The fifth stage of the circuit, updating memory, represents the actual write of a shot count to non-volatile memory. Therefore, successful operation of the round counter is defined by a nonzero current in the last stage of the circuit, which represents the firmware instructions required by the microcontroller to enter into a power saving sleep mode. All operations after the update to non-volatile memory are not essential to the operation of the round counter.

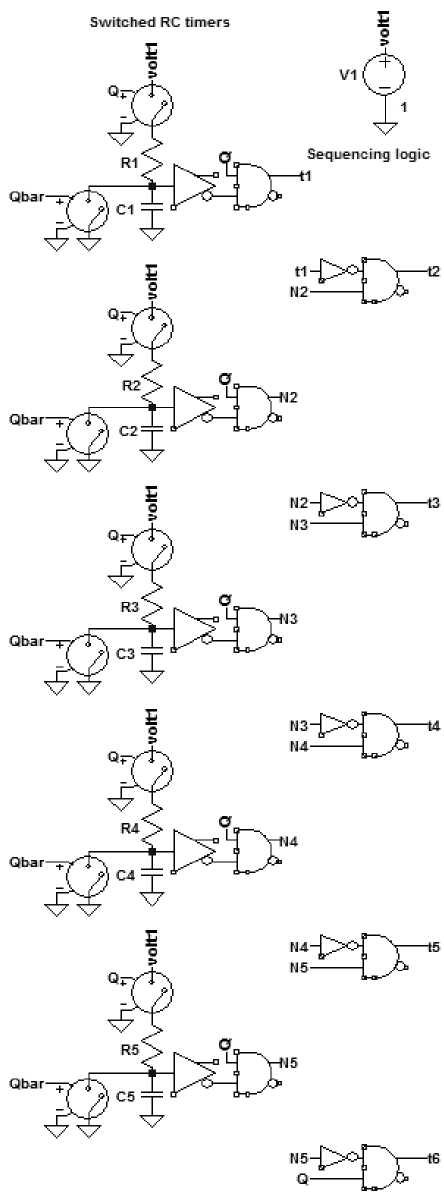

Figure 5. Timing logic

Figure 5 shows the timing logic used to control the switches in each stage. The timing is controlled by RC circuits with time constants, $\tau_{RC_n} = R_n C_n$, selected to ensure each stage is active for maximum execution time of each section of code, either measured experimentally or given in the microcontroller datasheet. Each τ_{RC_n} represents the cumulative time from when the chip turns on until a section is complete. As an example, τ_{RC_2} is the time required to execute both the first and the second sections of code. At start-up, ($V_{dd} > V_t$; $Q = 1$), all of the RC timing circuits begin to charge but only the first stage, controlled by the voltage at t_1, is on. When $t = \tau_{RC_1}$, the voltage at t_1 goes low and the voltage at t_2 goes high. At $t = \tau_{RC_2}$, t_2 goes low and t_3 is active. This sequence continues until the final stage is active. If at any time V_{dd} falls below V_{BOV}, all RC circuits are reset by Q_{bar}. In our firmware, the RC time constants were based on start-up times of 0.1 ms and 0.1 ms, 1 ms of A/D conversions, addressing logic time of 0.075 ms, and a non-volatile memory update requiring 5 ms.

DATA

The open circuit piezoelectric voltages were computed using data collected from live firing tests. Transducer voltages were measured for 5 shots each at 5 different energy levels. Figure 6 shows typical piezo voltage profiles for high and low energy shots.

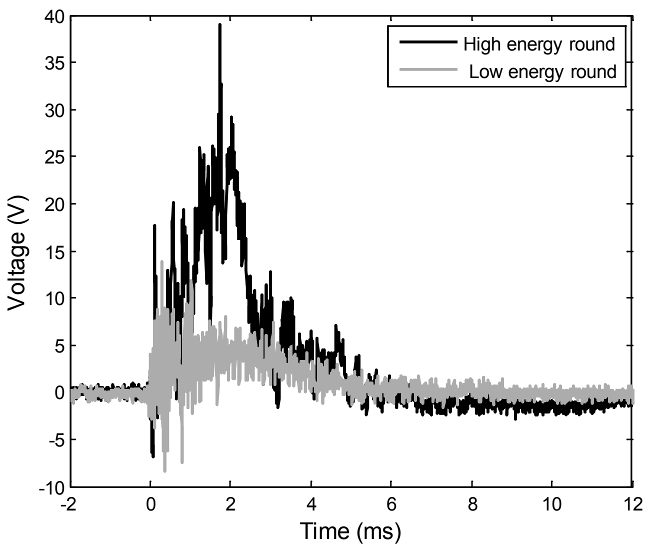

Figure 6. Typical piezoelectric signal profiles for high and low energy rounds

The piezo transducer strain associated with a shot is a single transient event which is considerably lower for low energy rounds. Therefore, there is less energy available to power the round counter circuitry. There is a direct correlation between this energy and the duration of the microcontroller supply voltage, V_{dd}. V_{dd} is generated by signal conditioning circuitry incorporating a low dropout voltage regulator and must remain above V_{BOV} until the non-volatile memory is updated. The impact of power loss during operation is mitigated by the BOR but could result in a missed count. While this effect can be partially managed in firmware, the most effective solution is a circuit that operates correctly even in a worst case scenario.

RESULTS

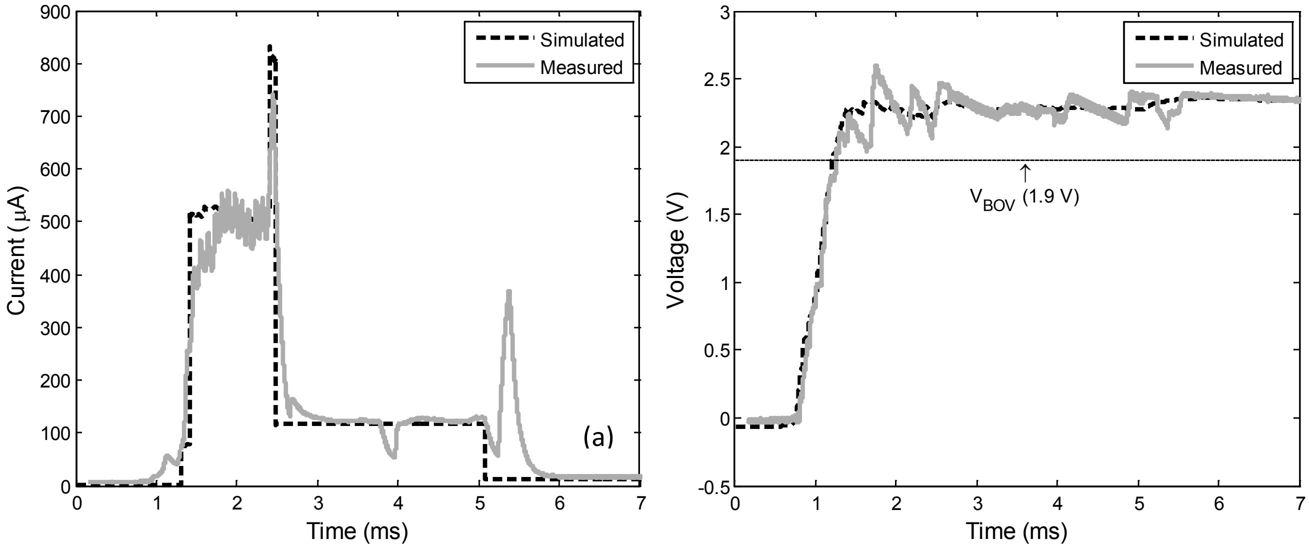

Figure 7. Comparison of simulated and measured power usage for the PIC12LF1822, low energy shot: (a) current (b) V_{dd}

Figure 7 shows a comparison of the simulated and measured current (a) and voltage (b) profiles using the measured piezo voltage for a low energy shot as input. The results are typical for all shots and show excellent agreement between simulation results and experimental data. The transient spike in current occurring at 5.5 ms is a result of operations necessary to put the microcontroller into sleep mode. This was not modeled because it occurs after a successful update to non-volatile memory.

LTSpice IV [5] was used to model the circuitry and a breadboard circuit was constructed to obtain the actual profiles. The open circuit piezo voltages were supplied to the circuit through a Piezo Systems EPA-104 linear amplifier using a series capacitor to represent the piezo film capacitance. A Tektronix DPO4104B oscilloscope and a Keithley 6485 picoammeter were used to record the profiles.

To quantify model accuracy, microcontroller energy usage was calculated as

$$E = \int_{t_{on}}^{t_{success}} V_{dd} \cdot I \, dt \qquad (1)$$

where t_{on} is the point at which V_{dd} first equals V_{BOV} and $t_{success}$ is the point at which the write is complete. The resulting energies for the plots in Figure 7 are $E_{simulated} = 2.021\ \mu J$ and $E_{measured} = 2.047\ \mu J$, a difference of 1.3%.

The LTSpice circuit model was used to find the minimum value of C_f required to update the cumulative count under worst-case conditions for all shots fired. Maximum time required for the firmware to complete a successful write to nonvolatile memory was calculated to be 6.25 ms, and it was determined that piezo voltages can vary by as much as 25% due to temperature and other effects. Figure 8 shows typical simulation results used to compute the length of time V_{dd} is greater than V_{BOV} for a high and a low energy round. This time duration was computed for each round at 75%, 100%, and 125% amplitude using LTSpice simulation results. Figure 9 shows Gaussian probability distributions fit to calculated time durations for all rounds using scaled piezo data and the minimum value of C_f. The minimum simulated time duration was 6.27 ms. From these results, it can be concluded that the microcontroller will have enough energy to complete a count increment in non-volatile memory for all shots using the selected value of C_f.

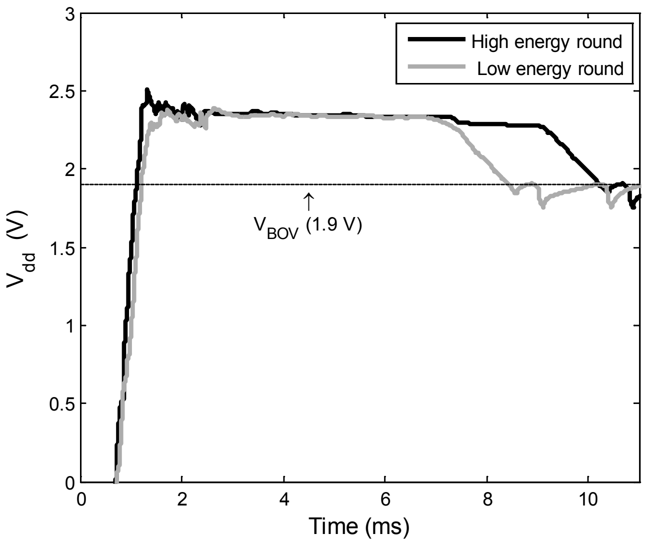

Figure 8. Typical simulation results used to determine the duration of $V_{dd} \geq V_{BOV}$, 100% amplitude

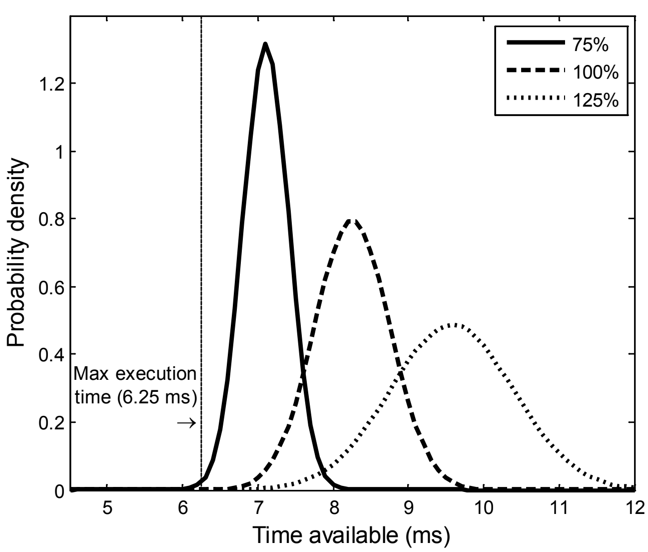

Figure 9. Probability densities representing the duration of $V_{dd} \geq V_{BOV}$ for all scaled piezo voltage data, $C_f = 7.2\ nF$

SUMMARY

A lumped-parameter modeling method has been developed that accurately simulates the time-varying and firmware specific power usage of a microcontroller. The model was implemented in LTSpice to optimize the design of an electronic round counter that employs piezoelectric transducers for power. A prototype round counter has been developed and successfully field tested using this approach. This technology reflects the Army's vision of eliminating reliance on batteries and provides a much needed capability to enhance soldier safety.

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BIOGRAPHIES

Sara Lorene Makowiec

Ms. Makowiec is an electronics engineer at Benét Laboratories. Her current research is focused on health monitoring technologies for gun tubes. She has worked with the Rensselaer Polytechnic Institute (RPI) Center for Terahertz Research and RPI Center for Earthquake Engineering Simulation as well as interning for General Electric Power & Water in steam turbine controls. She began working at Benét Laboratories as a co-op student and became a full-time employee after completing her BS in electrical engineering at RPI. Ms. Makowiec is currently pursuing graduate studies in electrical engineering at RPI with a focus on electromagnetic simulation of motors.

Mark Johnson

Mr. Johnson's current research is focused on developing new technologies for rapidly evaluating the health of gun tubes in the field He holds 8 patents and has authored over 70 publications. Mr. Johnson received a B.S. in Electrical Engineering and an M.S. in Computer and Systems Engineering from Rensselaer Polytechnic Institute.

Mark Doxbeck

Mr. Doxbeck received his B.S. degree, in Physics, from Rensselaer Polytechnic Institute, Troy, NY, in 1986. He has worked for Benet Laboratories since 1985. His current research interests include piezoelectric devices, developing firmware programs, and data acquisition and analysis.