A novel sensor based portable energy optimization method for battery powered electro-mechanical devices

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Word Count:

Abstract:
Galileo clock mechanisms maintain their relevance due to both their aesthetic appeal and the fascination with engineering and interest in STEM that they generate. However, an issue with its classic design is that its escapement is powered by the slow descent of a weight, and that weight must be reset often as it reaches the end of its range of motion. This leads to a loss of accuracy and requires hand holding. Alternatively, electro-mechanical Galileo based designs consume extensive power, due to a continuous running motor. I propose a novel energy efficient clock escapement design that uses optimization techniques via software control and hardware assisted power gating. I created a prototype using a commercial off-the-shelf microcontroller based embedded system, 3D printed motor housing, and sensors to turn off the battery when the pendulum is not in contact with the gear system and trade-off acceptable instantaneous accuracy. Interestingly even though the voltage does not drop to zero, at an average run frequency of 400 milliseconds, I proved via measurements and stratified over sampling, that no current is drawn. Thus, I achieved 44.2% energy savings that are linear in nature, hence continuous savings can be obtained over time. My design is portable, and can be applied to various mechanically driven applications such as a lawn mower and air compressor providing uninterrupted coverage of 6500 sq ft grass vs 4000 sq ft in former and nonstop runtime of 42 minutes vs 30 minutes in the latter.

Key Words:
Energy, Optimization, Escapement, Sensor, Electro-mechanical

Introduction:
Mechanical clock escapements have been around since the 13th century C.E. when Henry de Vick discovered how an oscillating mechanism could efficiently track time [6]. There are a variety of types of escapements that have been invented and improved over the past few centuries. Mechanical clock escapements are a way of telling time using a mechanism that oscillates at equal time intervals [7].The issue with many of these clocks is that they are weight driven, so they have a finite run time. Through this research, I designed an electromechanical Galileo clock escapement that tells time accurately and reliably and is energy efficient. The original electromechanical Galileo escapement consumes continuous large power. However, for most of the pendulum oscillation cycle, the motor is not required to be ‘on’ as the pendulum is not making contact with the gear train system. In this study, I opportunistically turn off the battery, thereby reducing power consumption.

Power has two components: dynamic power and leakage power and is a function of current (I) and voltage (V) as shown in Equation 1.

$$P = V * I$$

Equation 1. Power as a function of voltage and current

Voltage equals dot product of resistance (R) and current drawn (I) as shown in Equation 2.

$$V = I * R$$

Equation 2. Voltage per Ohm’s Law

Therefore, power is proportional to the square of current drawn as shown in Equation 3.

$P \propto I^2 * \mathrm{R}$
Equation 3. Power as a function of current

I keep leakage power constant while reducing dynamic power [8]. To save power, I turn off the motor entirely for a segment of the pendulum cycle, hence dropping the current to zero [12]. By saving power I also conserve energy, since energy is the integral of power as shown in Equation 4.

$E = \int P \, dt$
Equation 4. Energy as a function of power

Energy is directly related to the number of hours of battery life (HOBL) and therefore affects user experience while operating battery powered devices. My proposed energy optimization method can allow these devices to have extended battery life, and hence be in active use without power from the wall for longer periods of time. They would also require less frequent charging which will minimize interruptions for the user and improve operational efficiency along with user experience.

Methods

There are two key steps in this investigation: the design and fabrication of the clock mechanism and testing the clock mechanism for accuracy, efficiency, and reliability.

I began by creating a basic prototype of the Galileo clock escapement and analyzed the design's limitations as well as how the period of the pendulum could be used in an energy saving method [8]. I noticed a variation in the lengths of the period which was a result of the difference in the inertia during contact of pendulum to the gear as well as the coefficient of restitution [1]. Hence, I chose the 'average time period' metric for my analysis. Next, I measured the mass of the weight and radius of the spool to calculate the amount of torque that needs to be supplied by a motor. Multiplying the two yields the required torque, and this allows for proper sizing of a motor and gear train to power the clock mechanism. The motor and gear train need to be housed within the clock. To accomplish this, I custom built a housing whose dimensions are derived from the existing clock structure, designed it in SolidWorks, and 3D printed it. The motor housing design is shown in Fig. 1.

As shown in Fig. 2, the pendulum only interacts with the clock mechanism during the part of its swing when it is making contact with the gear train, so supplying torque to the system when the pendulum is not interacting with it will lead to energy losses. To mitigate this issue, I installed a sensing system on the clock using IR sensors. The arduino code runs such that when the sensor detects the pendulum the motor will stay off, and when the sensor does not detect the pendulum, and is therefore in contact with the gear system, the motor turns back on. This can be seen in lines 66-70 of the code shown in Fig 4. This will allow the system to supply the pendulum with its optimal energy to keep the clock running with a minimal amount of electricity being wasted. The electrical components of this system are controlled using a custom programmed Arduino Uno equipped with a motor shield.

Three attributes of the clock were tested in this investigation. The first of these being the accuracy of the clock ie. making sure the period of the clock is regular. To evaluate the energy efficiency of the clock, I measured the amount of electrical energy consumed by the clock with and without the sensing system over 30 cycles. I added an INA219 sensor that measures current, voltage, and power to the circuit. Of course, this task did not come without challenges, as it required difficult, precise re-soldering. Additionally, I had initially attempted to get current readings with a multimeter but the sampling interval did not provide data at granularity required for this approach, which is why I switched to the INA219. I modified the code such that the INA would attempt to get readings on the components listed above every 5 milliseconds as seen in line 13 of the arduino code in Fig. 3. However, the INA219 took readings every 7.5 milliseconds on average. The INA219 measured around 40-60 samples per cycle, so that sampling interval was tuned to get enough data for descriptive statistical analysis. By comparing these values I calculated expected improvement in energy efficiency due to the sensing system. Lastly, this system has been designed so that it will be more reliable than a Galileo clock escapement that is powered by a falling weight as it can have a much longer run time.

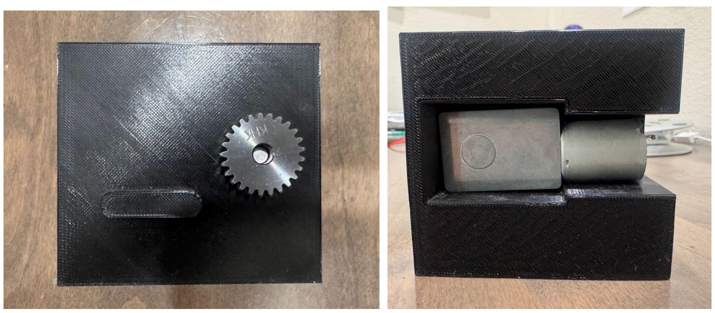

Fig. 1. Motor housing design with motor and gear

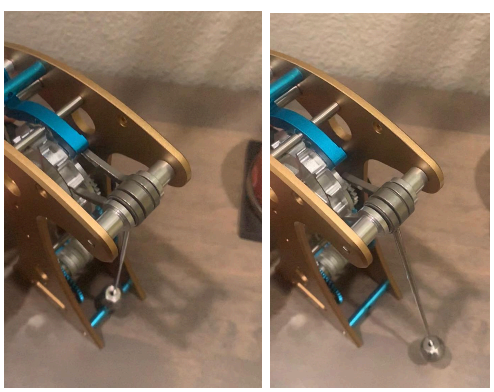

Fig. 2. Positioning of the pendulum when touching the gear system vs. when not in contact with the gear train

```cpp
#include <Wire.h>
#include <Adafruit_INA219.h>

Adafruit_INA219 ina219;

// -------------------- CONSTANTS --------------------
const int PIN_TO_SENSOR = 2;
const int MOTOR_DIR_PIN = 12;
const int MOTOR_BRAKE_PIN = 9;
const int MOTOR_PWM_PIN = 3;
const int ANALOG_PIN = A3;

const uint32_t SAMPLE_PERIOD_US = 5000; // 0.005 s = 200 Hz

// -------------------- TIMING --------------------
uint32_t nextSampleUs;

// -------------------- SETUP --------------------
void setup() {
  pinMode(PIN_TO_SENSOR, INPUT);
  pinMode(MOTOR_DIR_PIN, OUTPUT);
  pinMode(MOTOR_BRAKE_PIN, OUTPUT);
  pinMode(MOTOR_PWM_PIN, OUTPUT);

  Serial.begin(500000);
  Wire.begin();

  if (!ina219.begin()) {
    Serial.println("ERROR: INA219 not found");
    while (1);
  }

  // Optional: better resolution if you are below ~400 mA
  // ina219.setCalibration_16V_400mA();

  // CSV header
  Serial.println("t_s,sensor_digital,analog_val,bus_V,shunt_mV,current_mA,power_mW");

  nextSampleUs = micros();
}

```

Fig. 3. Arduino Code 1 (programs the INA219 and outputs of voltage, current, power, and sensor reading)

```cpp
// -------------------- LOOP --------------------
void loop() {
  uint32_t nowUs = micros();

  // precise 100 Hz scheduler
  if ((int32_t)(nowUs - nextSampleUs) >= 0) {
    nextSampleUs += SAMPLE_PERIOD_US;

    // ---------- TIMESTAMP ----------
    float time_s = nowUs / 1e6;  // seconds since boot

    // ---------- SENSOR READS ----------
    int sensorState = digitalRead(PIN_TO_SENSOR);
    int analogVal = analogRead(ANALOG_PIN);

    float busV     = ina219.getBusVoltage_V();
    float shuntmV  = ina219.getShuntVoltage_mV();
    float currentmA= ina219.getCurrent_mA();
    float power_mW = ina219.getPower_mW();

    // ---------- MOTOR LOGIC ----------
    digitalWrite(MOTOR_DIR_PIN, HIGH);
    digitalWrite(MOTOR_BRAKE_PIN, LOW);

    if (sensorState == HIGH) {
      analogWrite(MOTOR_PWM_PIN, 0);
    } else {
      analogWrite(MOTOR_PWM_PIN, 255);
    }

    // ---------- CSV OUTPUT ----------
    Serial.print(time_s, 4); Serial.print(",");
    Serial.print(sensorState); Serial.print(",");
    Serial.print(analogVal); Serial.print(",");
    Serial.print(busV, 6); Serial.print(",");
    Serial.print(shuntmV, 6); Serial.print(",");
    Serial.print(currentmA, 6); Serial.print(",");
    Serial.println(power_mW, 6);
  }
}
```

Fig. 4. Arduino Code 2 (programs the motor such that it will turn off when the sensor detects the pendulum)

Results

The experimental results demonstrate that selectively actuating the power supply using the sensor system significantly reduces energy consumption. A similar technique was used in a different study optimizing algorithms to reduce power consumption in VLSI circuits; my project uses a near identical algorithm of turning off voltage supply when it is not needed [3]. The tradeoff for this energy savings was a modest increase in the variance of the oscillation period [3].

Across all sensor-controlled operations, the battery supply was disabled for approximately 42.2% of each oscillation period. The rise and fall times of the measured current were observed to be effectively zero within the resolution of the INA219 measurement capabilities, indicating that the switching behavior of the system was nearly instantaneous. This suggests that the observed power reduction was due to a discrete on/off actuation of the motor.

As seen in Fig. 5, 6, and 7, a modest increase in the variance of the oscillation period was observed in the sensor-controlled tests compared to continuous motor operation. The increased variability from 0.02 sec for continuous operation to 0.06 sec for the sensor-controlled operation is due to intermittent contact dynamics between the pendulum and the gear system in the mechanical design [2]. When power is applied only during particular phases of the oscillation, small differences in the timing of the engagement produced measurable fluctuations in the cycle period. This variance was evenly spread across the simulation with no clear pattern of the oscillations becoming shorter or longer over time, demonstrating that the mean oscillation period remained stable over the duration of the simulation. Interestingly, the mean cycle period increased by 40 ms during the sensor-controlled operation. For an ideal small-angle pendulum, the period is independent of amplitude and only depends on the mass of the bob and pendulum length. However, this system is not ideal for several reasons including the mechanical coupling of the motor and gears and the intermittent forcing of the pendulum. By turning off the motor for portions of the cycles, the pendulum spent more time near its amplitude, effectively increasing the period. The period increase of 14.3% (28 milliseconds continuous operation vs. 32 milliseconds sensor-controlled operation) indicates that the system is still receiving sufficient energy to sustain oscillations, with the sensor-controlled actuation still preserving the functional motion. So any energy savings are achieved without ultimately destabilizing the system. This is important for many real-world applications since many use cases do not require precise timing as long as the system is stable.

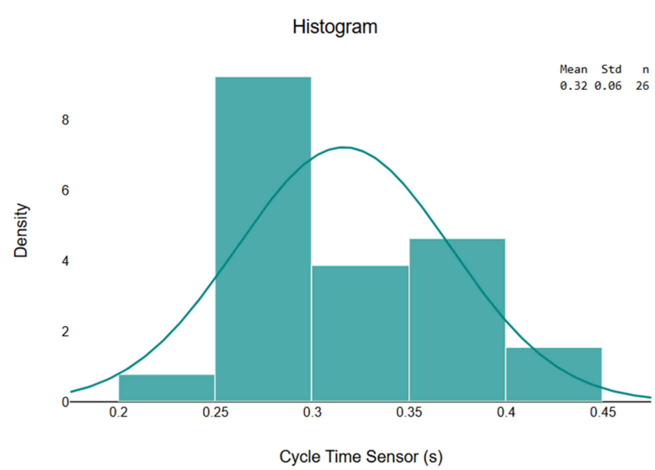

Fig. 5. Measurements of cycle times with power optimization system

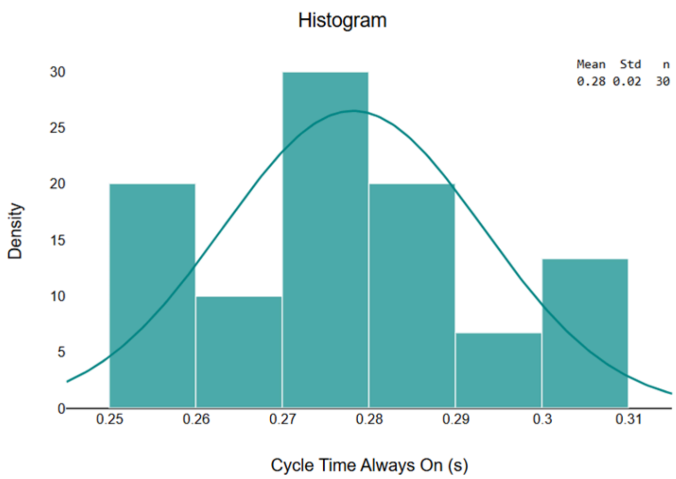

Fig. 6. Measurements of cycle times without power optimization system

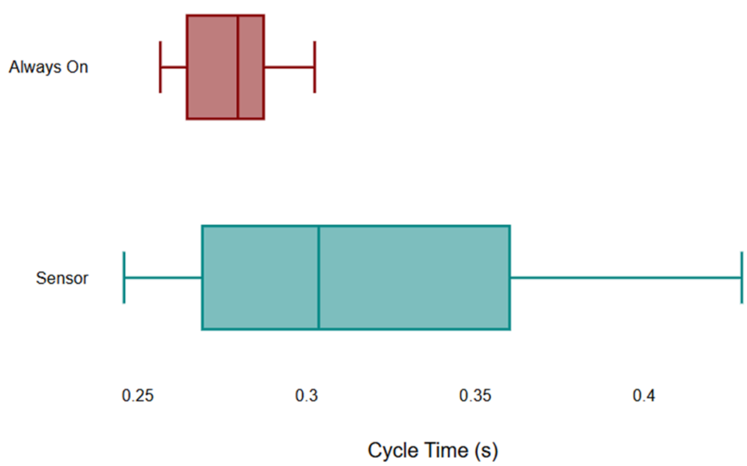

Fig. 7. Comparison of standard deviations of cycle times with power optimization vs. without

Fig. 8 and 9 show representative time-series measurements across the motor from the INA219 circuit of voltage, current, and power during sensor-enabled trials. When the sensor detected the pendulum, the current measurement dropped to 0 mA, confirming the complete stop of electrical current flow to the motor. During these intervals, the bus voltage across the INA219 also dropped. The measured power closely followed the current, consistent with the relationship described in Equation 1. When current dropped to zero, the power also dropped to zero. Small transient spikes observed during switching are measurement noise and rapid switching dynamics as the motor has to overcome the system's inertia and begin rotation [1].

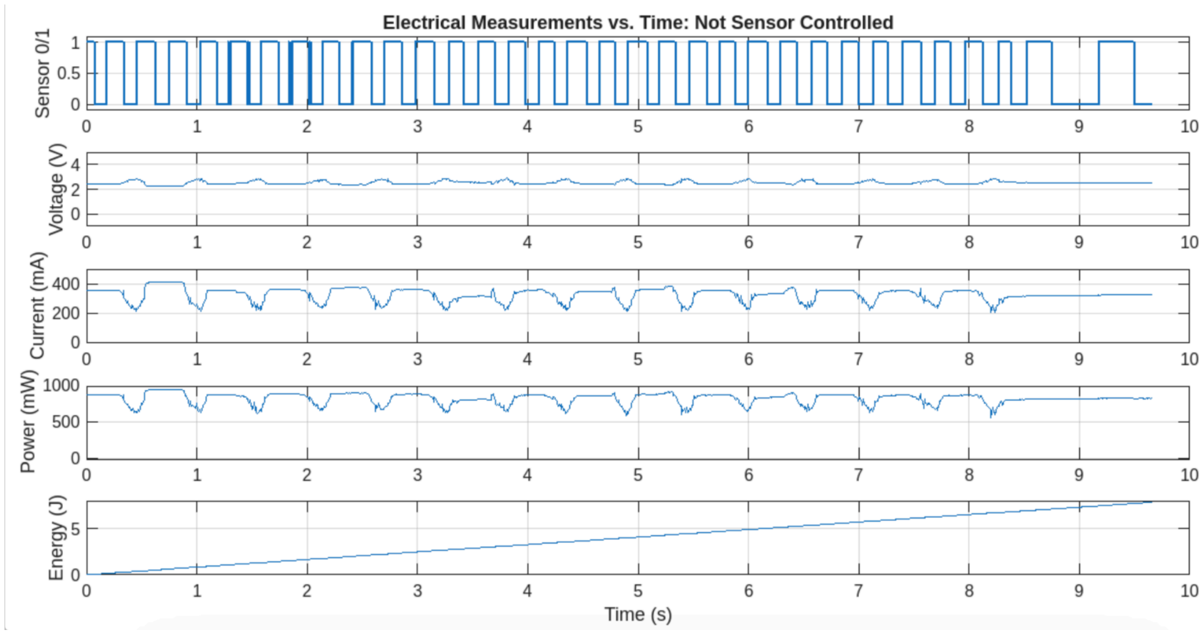

Fig. 8. Graphs of electrical measurements taken by INA219 circuit without power optimization method

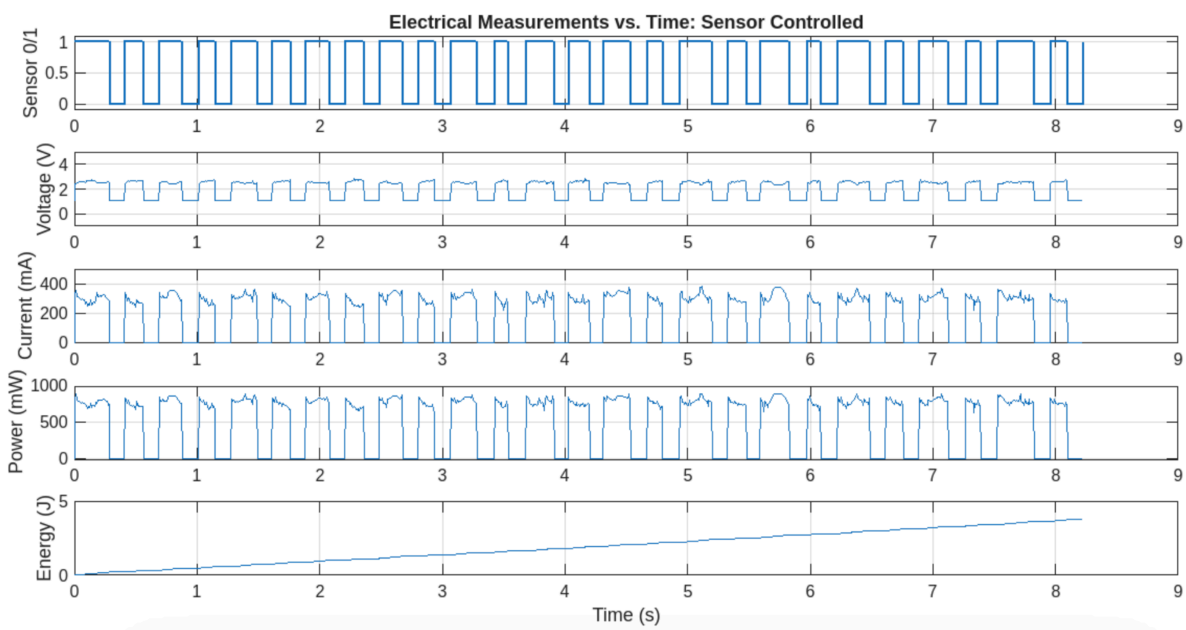

Fig. 9. Graphs of electrical measurements taken by INA219 circuit with power optimization method

Fig. 10 compares the cumulative energy consumption with and without the sensor during an extended interval. The energy difference between the two configurations show a linear trend since the sensor triggers the battery to be disabled for a constant fraction of each oscillation. I achieved average energy savings of 44.2% over the duration of the experiments.

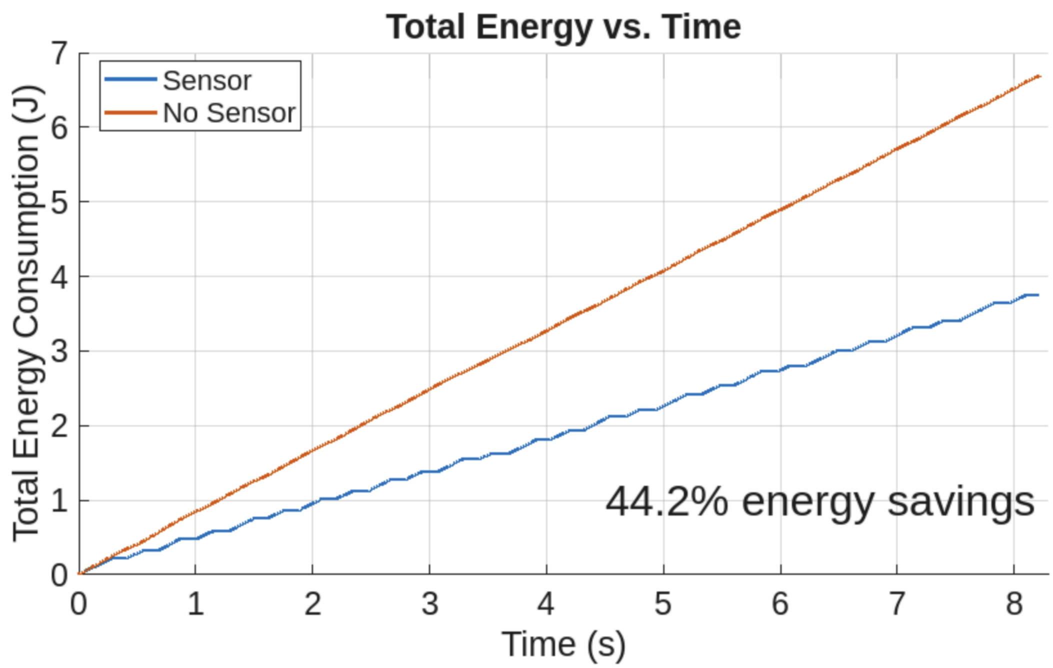

Fig. 10. Comparison of total energy consumed during runtime with power optimization method vs. without

As shown in Equation 5, I used a linear regression model to relate the energy consumed per cycle to the duty cycle of the motor. My results demonstrate that energy per cycle remains statistically constant, and consistent with the motor being inactive for 42.2% of each cycle. Per the residual analysis, remaining variation is minimal and can be attributed to noise rather than system behavior.

$$E_{cycle} = \boldsymbol{\beta}_0 + \boldsymbol{\beta}_1(on - time\ fraction) + \varepsilon$$

Equation 5. Linear regression relating duty cycle to energy consumed

Discussion

Compared to other similar research such as an Atmos clock, my model and setup differs in that it is driven by motor vs atmosphere and hence an electro-mechanical escapement control system rather than a purely mechanical device [8]. Additionally, both the POWSER based system and my approach traded off acceptable accuracy in order to save energy [4]. POWSER achieved 34% power savings, while my work obtained 44.2% energy savings.

To further this study, I plan to minimize design issues by tuning the pendulum length and mass such that it does not vary when in the cycle it is engaged with the gear system, keeping the cycle times consistent. To further optimize energy savings, I will experiment with how many cycles the pendulum can run without needing a boost of energy from the motor, allowing for longer periods of time where power supply is not needed and saving significantly more energy. I also plan to utilize a **x** to ensure all energy comes from the battery.

Additionally, I plan to simulate and test my power optimization method in real world applications to measure obtained savings vs. expected savings determined by Equation 1. I will also measure the increase in uninterrupted runtime. One of these ideas include electric lawn mowers that stop running when they sense a dead patch of grass or already cut grass.

For a RYOBI mower, with rating of 40V and 40 amps current, applying equation 1, power consumed in continuous mode is 1600W. This approach can reduce power to 892.8W, thereby extending active time use by 1.6x. Max advertised runtime is 80 minutes. Push mowers cut ~3000 sq ft of grass per hour. For the St Augustine variety, 40% grows faster than the rest. By implementing the power optimization technique on a RYOBI mower the runtime could increase to 128 minutes and could cover 6400 sq ft with sustained use.

Another application is a reciprocating air compressor. The compression stroke demands the most torque but the intake stroke requires little [11]. The motor could assist during the compression stroke. This could lower the peak motor sizing, reducing weight, cost, and wear.

For instance, applying this sensor based system to a VIAIR brand air compressor with a rating of 24 V and 23 amps current, can save up to 243 W based on calculations from equation 1. The recommended runtime for a VIAIR air compressor is 30 minutes. Through this energy optimization method the runtime could be increased to 42 minutes.

Other applications could be pumps which usually consist of a piston and a DC motor. Near the top dead center of a cycle or bottom dead center there is approximately zero torque so any energy injected into the system is mostly wasted [5]. Conversely, energy put into the system mid-stroke will provide maximum torque and is highly efficient. Lastly, this power optimization method could be used as a hybrid assist on single-cylinder engines. Combustion engines are usually non-uniform and the crank can stall near top dead center or bottom dead center. A DC motor could be applied to provide an electric assist only near these positions and off during the power stroke [13].

Conclusion

Ultimately, through this project I found that my sensor power optimization method proven on a Galileo clock escapement can save up to 44.2% energy compared to the system running off a motor continuously. This power optimization technique can be applied to many relevant, and potentially complex systems where the power supplying the system is not needed during idle time. This can not only save energy, but enhance user experience due to longer continuous lawn coverage of 6400 sq ft, if applied to household items such as an electric lawn mower. Similarly, for an air compressor the sustained runtime increases from 30 minutes to 42 minutes.

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