A Method to Quantify Energy-Stability Tradeoffs Using Sensor-Controlled Actuation in a Galileo Escapement

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Key Words

Galileo clock escapement, electromechanical system design, energy efficiency, energy-stability tradeoff

Overview

This project investigates how selectively applying power during specific phases of motion can reduce energy consumption in cyclic electromechanical systems while preserving stable operations. Using an electromechanical Galileo clock escapement as a test system, we developed a sensor-controlled actuation method and experimentally measured the tradeoff between energy efficiency and oscillation period consistency. The results demonstrate that substantial energy savings can be achieved through intermittent actuation.

Summary

Many oscillatory mechatronic systems are powered continuously despite requiring mechanical energy only during specific phases of motion, leading to unnecessary energy consumption. In this study, we investigated whether selectively engaging power can reduce energy use while maintaining stable behavior. The central hypothesis was that intermittent, sensor-gated motor activation would significantly lower total energy consumption at the potential cost of increases in oscillation period variability and long-run stability. To test this, we constructed an electromechanical Galileo clock escapement with a position-sensing system that enabled motor power only when mechanical energy input was required, and we measured energy consumption and oscillation behavior under both continuous and sensor-controlled operation. The results showed that sensor-gated actuation reduced measured energy consumption by an average of 44.2% while introducing increases to both the mean and standard deviation of the oscillation period, with stable operation maintained throughout testing. Our findings demonstrate a practical, measurement-based method for how to quantify energy-stability tradeoffs in periodic mechatronic systems and show how selective actuation timing can improve efficiency in applications where precision timing is not required.

Introduction

Cyclic electromechanical systems are widely used in applications ranging from clocks to pumps, compressors, and actuated linkages. In these types of systems, mechanical energy is often required only during specific phases of each operating cycle, but electrical actuators are often driven continuously. This design leads to unnecessary energy consumption, particularly in battery-powered systems where efficiency is directly proportional to runtime.

Prior work on microcontroller-based sensor systems has shown that disconnecting power to inactive components through power gating can significantly decrease energy consumption [1]. However, applying power selectively introduces a fundamental tradeoff between energy efficiency and both the timing consistency and stability of the system. In oscillatory systems, such as pendulum-driven mechanisms, applying torque to the system intermittently can alter the oscillation period and increase variability across periods. Prior analytical studies of mechanical clock escapements have shown that oscillation behavior is strongly influenced by collision dynamics, inertia, and energy transfer during discrete mechanical interactions, even under stable operating conditions [2]. Quantifying this tradeoff is therefore essential for evaluating any practical use of energy-saving selective powering strategies. While approaches such as duty-cycle modulation and event-driven control are widely used, our study focused on developing an experimental framework for characterizing energy-stability tradeoffs in a small-scale electromechanical system rather than on comparing our system with other implementations and prior studies.

In this study, we developed a measurement-based system to evaluate the tradeoff between energy efficiency and oscillation period consistency mechatronic systems. We demonstrated a framework using an electromechanical Galileo clock escapement with proximity-sensor driven motor timing. By comparing continuous and sensor-controlled operation, we quantified changes in energy consumption, mean oscillation period, and period variability. This approach provides a method for assessing energy-stability tradeoffs and establishes a foundation for evaluating actuation optimization in periodic electromechanical systems.

Results

To evaluate the effect of phase-dependent actuation on both energy consumption and oscillatory behavior, we chose measurements to directly compare continuous motor actuation and sensor-controlled actuation within the same mechanical system. Because selectively disabling motor power reduces on-time while altering the timing of the energy input, energy consumption and oscillation period consistency provide metrics that can be used to assess the tradeoff. We collected measurements across multiple oscillation cycles for both continuous and sensor-controlled modes, and results are reported in terms of energy usage, oscillation period mean and standard deviation, and observed electrical and mechanical behavior over time.

When sensor controlled, we positioned the sensor to disable motor power for an average 42.2% of each oscillation period, attempting to best match the timing of the motor to when the pendulum system was in contact with the gear train. Transitions between powered and unpowered states occurred with rise and fall times less than the resolution of a INA219 current and voltage measurement system, indicating that the switching behavior of the system was nearly instantaneous. This suggests that the observed power reduction was due to discrete on/off motor actuation as compared with gradual ramping.

Figure 1 compares the cumulative energy consumption with and without the sensor-based controller over 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 nearly constant fraction of each cycle. Average energy savings of 44.2% were achieved over the duration of the experiments, in line with the percentage of time that the motor was disabled.

Oscillation period measurements revealed differences in both the mean period and the variability of cycle times between actuation modes. Figure 2 shows representative cycle period measurements under both continuous and sensor-controlled operation. Additionally, Figure 3 compares the corresponding distributions. Under continuous motor operation, the oscillation period exhibited low variability, with a measured standard deviation of 0.02 s. However, when sensor-controlled, the standard deviation increased to 0.06 s. This increase in variability was observed consistently across trials and did not drift over time, indicating that oscillatory behavior remained stable within the presented ranges throughout all trials. In addition to increased variability, sensor-controlled actuation produced an increase in the mean oscillation period. The mean period increased from 28 ms under continuous operation to 32 ms under sensor-controlled operation, a 14.3% increase.

Figures 4 and 5 consist of time-series measurements of voltage, current, and power under both continuous and sensor-enabled trials. In the sensor-controlled mode, current measurements dropped below the resolution of the INA219 sensing system when power was disabled to the motor, so these current measurements were treated as effectively zero when calculating power. Transient spikes observed at switching boundaries were brief and small in magnitude. We attributed the transient behavior to the motor’s starting dynamics, such as inrush current, and concluded that since this transient behavior was negligible, reductions in total energy consumption arose almost entirely from reduced motor on-time.

Discussion

Our study demonstrates that sensor-controlled, phase-dependent actuation can substantially reduce energy consumption while altering oscillation timing behavior in predictable ways. By experimentally comparing continuous and sensor-controlled operation within the same system, the results quantify a clear tradeoff between energy efficiency and oscillation period consistency and provide a general framework for optimizing designs in similar oscillatory devices.

The observed increase in mean oscillation period and cycle-to-cycle variability under sensor-controlled actuation is due to the non-ideal dynamics of a repetitively forced pendulum system. Unlike an ideal pendulum, our system included a coupling of the pendulum with a motor and gear train with inputs of energy only applied during specific phases of motion. Small variations in engagement timing during these phases likely contributed to the measured increase in variability. We observed that the timing of the engagement of the gear train and pendulum would deliver unequal energy transfer as compared to the continuous operation, leading to some cycles to be considerably longer. Despite this, sensor-controlled behavior remained bounded and stable over extended operation, indicating no drift of the period or loss of function of the pendulum over time. More generally, escapement-based systems require the effective strength of actuation to be tuned so oscillations are sustained without producing excessive amplitudes that could lead to interference or instability, and the need to balance sustained oscillation with amplitude constraints is consistent with previous control gain analyses of clock escapements and helps explain why changes in actuation timing can influence stability and period consistency [3].

Prior investigations of mechanical clock escapements have demonstrated the importance of contact dynamics, inertia, and gear coupling on energy transfer and stability in escapement systems. Specifically, detailed experimental and numerical analyses of mechanical escapements have shown that subtle variations in mechanical interaction forces can lead to variations in period in real conditions. For example, some escapement designs introduce forces on the escape wheel which causes it to recoil on contact [4]. This behavior leads to inefficiency and an increase in variability in oscillation periods.

This context supports the interpretation that the increased period variability observed under sensor-controlled use in our study arises mostly from the mechanical dynamics of the escapement rather than from electrical actuation. Several factors may have influenced the measured results. Parameters such as sensor placement, activation duration, and battery voltage were held constant in order to isolate the factors that could be used to analyze the energy-stability tradeoff. Mechanical losses due to friction, gear recoil, and variations in contact dynamics may also have contributed to oscillation variability. Our measurement resolution limited our ability to resolve very small changes in motor power during contact events, but we hypothesize that the pendulum was able to settle into a more consistent swing under continuous operation due to the gear train and pendulum being able to synchronize. Further investigation would be necessary to explore how the intricacies of these contact dynamics influenced our results.

The significance of our findings lies in the demonstration of a practical method for quantifying energy-stability tradeoffs in cyclic electromechanical systems more generally. Rather than optimizing a single metric such as energy efficiency, our framework enables a direct comparison of actuation strategies using experimentally measured power consumption and cycle period variability. This perspective is relevant to a wide range of systems in which extended runtimes or reduced energy consumption are prioritized over precision and accuracy. Examples include a variety of electromechanical, oscillatory systems such as electric air pumps, piston-driven pumps that use DC motors, and electric lawn mowers.

Several scientific and engineering questions remain open about our work. Future studies could systematically vary parameters such as duty cycle, sensor phase, and motor torque to map a broader range of operating conditions. Applying the same evaluation framework to other oscillatory mechanical systems would help determine how system geometry, inertia, and mechanical coupling influence observed tradeoffs. The sensitivity of escapement timing to mechanical coupling and contact dynamics suggests that future work aiming to reduce period variability should consider mechanical design refinements in addition to electromechanical control using position sensors.

Overall, our work shows that phase-dependent, sensor-controlled actuation can significantly reduce energy consumption while maintaining stable oscillation behavior in a DC motor powered Galileo escapement. By quantifying the relationship between energy use and timing consistency, the study provides a general experimental approach for evaluating efficiency-stability tradeoffs in electromechanical systems.

Methods

Our investigation consisted of two stages: first, we designed and fabricated the clock mechanism, and second, we experimentally tested the clock mechanism for efficiency, accuracy, and stability.

We prototyped a Galileo clock escapement to allow controlled electromechanical actuation, and we evaluated to see how the pendulum's period could be leveraged for energy savings. During initial testing, the variability in the pendulum's period seemed to result from the difference in the inertia during contact of the pendulum to the gear as well as the coefficient of restitution [5]. Because this variability is inherent to pendulum systems with intermittent forcing, we selected the mean oscillation period and period standard deviation as the primary metrics for evaluating timing consistency.

To properly size the motor and gear train, we measured the mass of the clock's driving weight and radius of the spool to estimate the torque required to sustain oscillations. This approach follows established analyses of weight-driven clock mechanisms in which torque applied to the gear train is determined by a driving mass under the influence of gravity [6]. Informed by these measurements, we selected a DC motor and gear reduction sufficient to maintain stable operation without excess torque. Next, we designed a custom motor housing to integrate the motor and gear train within the existing clock structure. The housing, shown in Figure 6, was modeled in Solidworks and fabricated using a 3D printer.

Mechanical energy is only transferred from the gear train to the pendulum during the portion of the oscillation cycle when the two are in contact as shown in Figure 7. Supplying motor torque outside of this interval contributes no useful work and results in unnecessary energy consumption. To address this inefficiency, we implemented a position-based sensing system to power the motor only during the engagement phase of an oscillation cycle.

We mounted an infrared sensor to detect the pendulum's position relative to the gear train. We used the sensor output to control motor power such that electrical actuation was only enabled during portions of the oscillation cycle when mechanical energy was useful. During intervals when the pendulum was not interacting with the gear train, we disabled the motor power. This approach ensured that energy was supplied only when it contributed to powering the pendulum and sustaining oscillations.

We managed all sensing, control, and actuation functions with an Arduino Uno microcontroller with an integrated motor driver. We wrote a simple control logic to maintain consistent behavior across all oscillation cycles, activating the motor only during portions when the sensor was triggered.

We evaluated energy consumption by measuring voltage and current delivered to the motor under both continuous actuation and sensor-controlled actuation. Initial measurements using a standard multimeter did not have the sufficient resolution to see rapid changes in current associated with the system. To obtain better resolution, we implemented a more capable INA219 power-monitoring sensor, with the final system configuration shown in Figure 8.

We evaluated three performance attributes of the clock: energy consumption, oscillation period consistency, and operational stability. We measured energy efficiency by comparing the total energy consumed per cycle for both continuous operation and sensor-controlled engagement. We calculated the total energy consumed by integrating the power measurements from the INA219 sensor over time. We evaluated the oscillation period consistency using the standard deviation of the oscillation period over many cycles. Lastly, we evaluated operational stability by looking for any drift in the oscillation period over an extended runtime.

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Tables and Figures

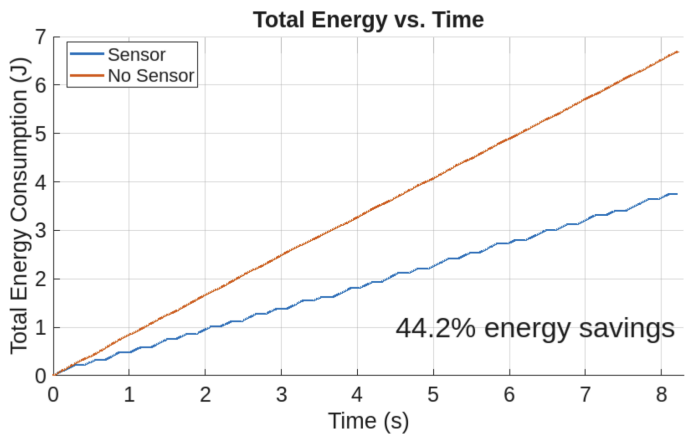

Figure 1. Cumulative energy consumption under continuous and sensor-controlled actuation

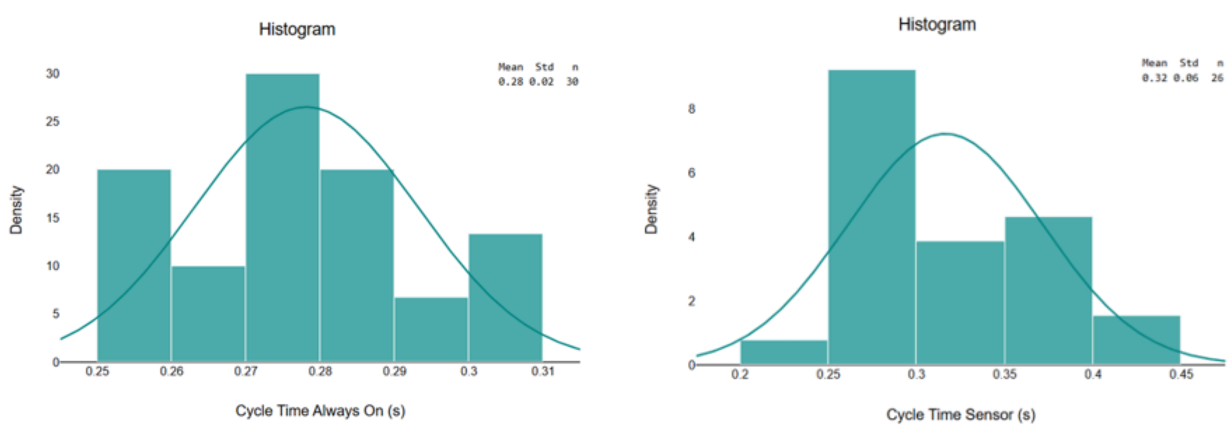

Figure 2. Cycle period distributions for both continuous and sensor-controlled actuation

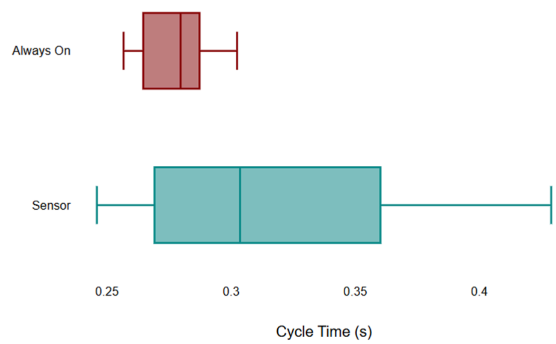

Figure 3. Oscillation period comparison: Continuous operation vs. Sensor-controlled operation

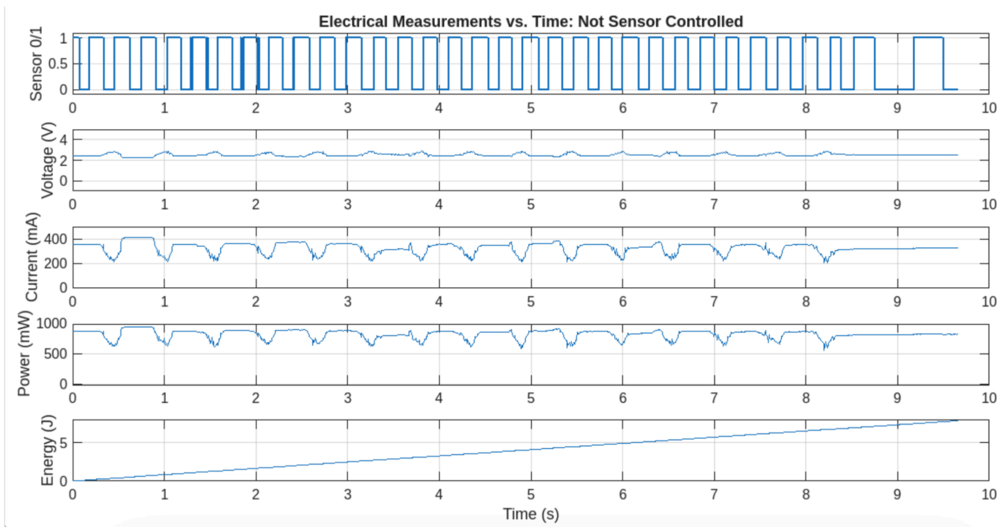

Figure 4. Time-series electrical measurements under continuous motor actuation

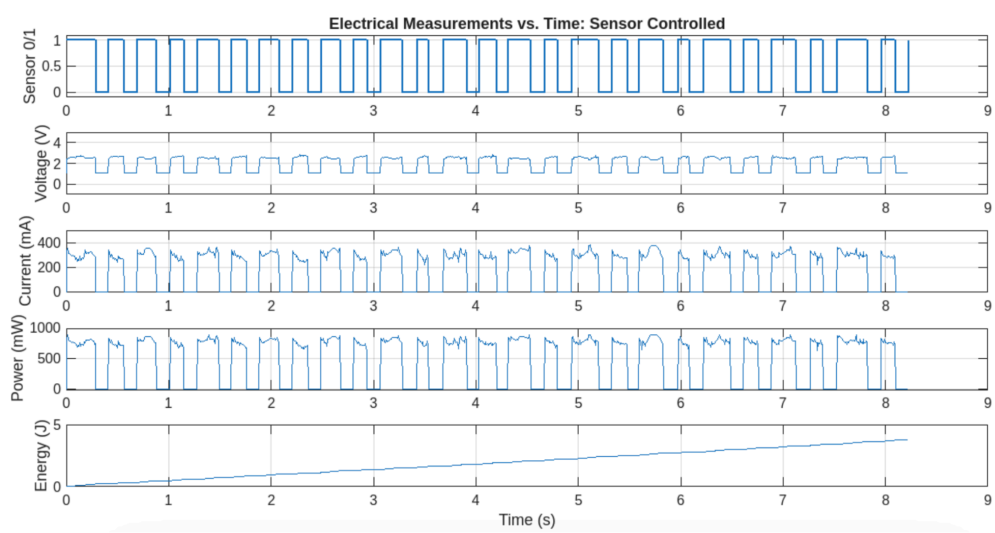

Figure 5. Time-series electrical measurements under sensor-controlled actuation

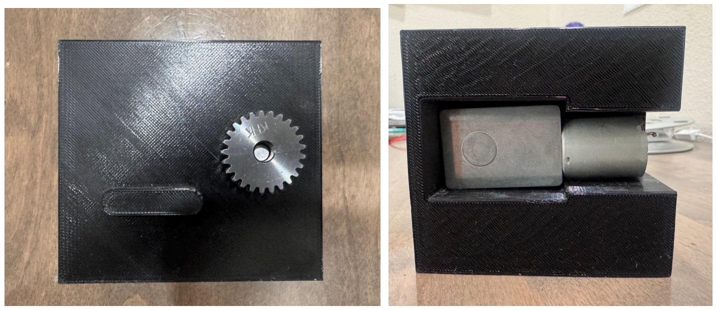

Figure 6. Motor housing design with motor and gear

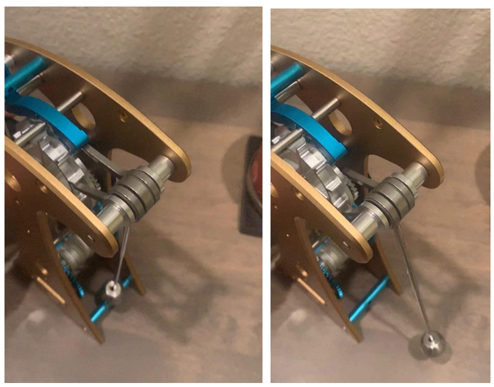

Figure 7. Pendulum-gear engagement and non-engagement phases during oscillatory motion

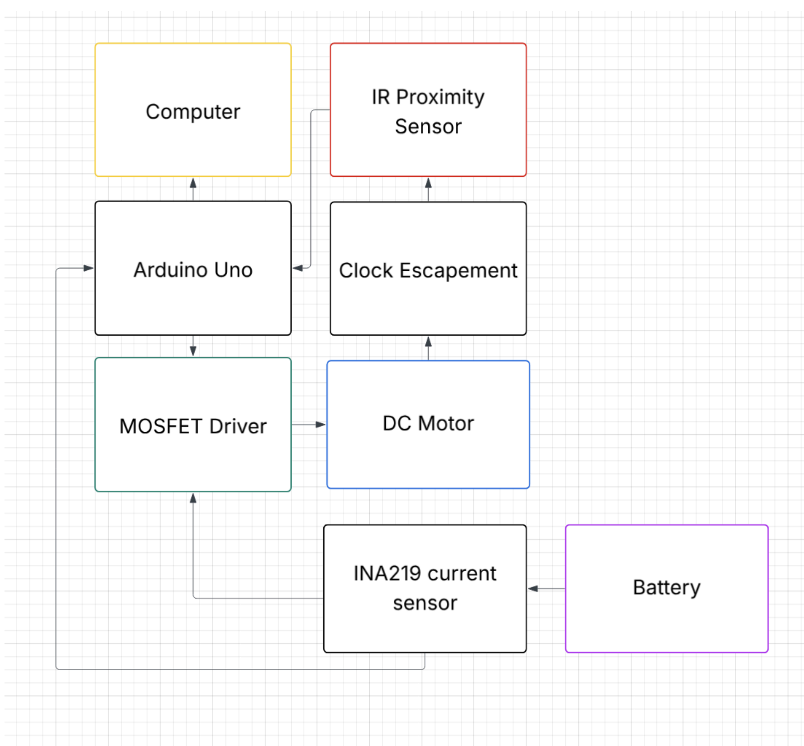

Figure 8. System Block Diagram