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Lock in Amplification and Synchronous Detection Based on Arduino

Yuanliang Sheng

Brunel London School, North China University of Technology, Beijing, China
22190020306@mail.ncut.edu.cn

Abstract. Accurate detection of weak light signals in noise is a key problem in the field of science and technology. While advanced techniques such as SPAD and conformance checking provide high performance, they are usually complex and costly to operate. This study investigates a cost-effective alternative by implementing the digital lock-in amplifier algorithm on an accessible Arduino Uno microcontroller. This study explores the feasibility and effectiveness of this low-cost approach in recovering weakly modulated optical signals subject to significant environmental noise through dynamic video screen simulations. Based on Arduino, the system uses optical signal modulation, custom digital phase-locked algorithm for synchronous demodulation, and serial data transmission for analysis. The experimental results show that the proposed method can successfully extract the 1000 Hz modulated LED signal from the highly noisy sensor data, and the significant attenuation of spectral noise is verified by Simulink simulations. The study highlights the potential of this low-cost implementation in applications where cost-effectiveness is critical, such as educational tools and basic environmental sensing, while acknowledging limitations in real-time applications due to the inherent processing and serial communication delays of the Arduino platform. The consistency between the experiment and simulation results verifies the effectiveness of the digital lock-in amplifier based on Arduino for weak signal recovery in noisy environments.

Keywords: Lock-in Amplifier, Synchronous Detection, Arduino, Optical Sensor, Signal Processing

1. Introduction

Accurate and efficient detection of weak light signals in noisy environments is a crucial capability in various scientific and technological fields. Identifying and quantifying subtle light changes is often fundamental to key advances and measurements, from environmental monitoring, biomedical communications to industrial automation, and fundamental physics research. For example, in environmental monitoring, detection of trace pollutants such as polycyclic aromatic hydrocarbons (PAHs) in water samples using fluorescence spectroscopy relies on small changes in light emission after locked excitation. The ability to accurately measure these weak fluorescent signals, even in the presence of background light and scattering, is important for assessing water quality and identifying potential health risks. Similarly, in biomedical diagnostics, the identification of disease biomarkers,

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such as the concentration of specific proteins indicative of early-stage cancer detected by elisa of fluorescent or luminescent reporters, often involves the analysis of weak fluorescent or luminescent signals. These signals can be very weak and sensitive detection methods are needed to distinguish them from autofluorescence inherent to biological tissues or reagent background noise. Today's growing demand for highly sensitive and low-noise optical detection systems highlights the importance of continuing to develop and improve methods that can overcome the inherent limitations caused by noise interference.

Remarkable progress has been made in the field of weak light signal detection through various advanced technologies. Researchers have explored advanced photodetector technologies with inherently low noise properties. For example, SPADs have demonstrated exceptional sensitivity, capable of detecting individual photons, achieving photon number resolution, and exhibiting picosecond-level timing accuracy, making them optimal for applications like quantum key distribution and fluorescence lifetime imaging microscopy [1]. In addition, coherent detection methods, such as heterodyne and homodyne detection, have been successfully employed to enhance the signal-to-noise ratio (SNR) by orders of magnitude (e.g., achieving >20 dB improvement in specific experiments) by mixing weak signals with strong local oscillators, enabling the extraction of both amplitude and phase information with high precision, crucial for fields like optical coherence tomography and high-sensitivity spectroscopy [2]. These techniques often require complex optical setups and specialized hardware. The lock-in amplifier principle has been extensively studied and implemented in the context of simpler and more economical solutions. This method exploits the correlation between the modulated signal and the synchronous reference to selectively amplify the signal of interest while rejecting noise at other frequencies [3]. In industrial settings, cost-effective lock-in amplifiers are employed for tasks such as detecting the modulated signal from a flame sensor in safety systems or measuring the impedance of sensors in process control, showcasing their practicality in budget-conscious applications. This method exploits the correlation between the modulated signal and the synchronous reference to selectively amplify the signal of interest while rejecting noise at other frequencies. Although traditional analog lock-in amplifiers provide high performance, their hardware complexity and cost have greatly limited in the program.

This study aims to produce a cost-effective and adaptable method for weak light signal detection by implementing the digital lock-in amplifier algorithm on an easily available Arduino Uno motherboard. The main objective of this study is to demonstrate the feasibility and effectiveness of this low-cost digital implementation to recover weakly modulated optical signals in the presence of noise.

2. Method

In this study, the synchronous detection technique is used to extract the modulated optical signal from the noisy environment. The core method involves generating a modulated light source, converting the optical signal to an electrical signal, and then synchronously demodulation using a digital lock-in amplifier algorithm implemented on an Arduino Uno, which is an open-source microcontroller board based on the user-friendly ATmega328P. It features 14 digital I/O pins, 6 analog inputs, and a USB connection, commonly used for electronics prototyping and education.

2.1. Experimental materials

The following materials are used in this experiment:

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The Arduino Uno development board, a microcontroller board, was utilized to generate Light-emitting diode (LED) modulation signals and implement the digital lock-in amplifier algorithms. The DFRobot FIT0031 Analog Ambient Light Sensor, an analog output optical sensor, was employed to detect the light emitted by the LED and convert it into a proportional voltage signal. A high-brightness LED served as the modulated light source for the experiment. A Current limiting resistor, connected in series with the LED to protect it from excessive current, had a resistance value chosen based on the LED's specifications and the Arduino's output voltage (a 10-ohm resistor was selected for this experiment). A breadboard and connecting lines were used for prototyping the circuit and connecting the various electronic components together. Finally, the Arduino IDE software was used for programming the Arduino Uno and for visualizing the experimental data via a serial plotter. Finally, Simulink is used for simulation.

2.2. Experimental methods

The study employs optical signal modulation and synchronous detection to isolate a weak signal from noise. An Arduino Uno generates a PWM signal to modulate an LED, and a FIT0031 sensor detects the light and noise, converting it to voltage. A digital lock-in amplifier algorithm on the Arduino then processes this, synchronized to the LED modulation for selective amplification and noise rejection.

To evaluate the robustness of this approach under challenging real-world conditions, the experimental design incorporated a dynamic noise source. Specifically, the final product was placed in front of a screen displaying a brightly colored video. This setup aimed to simulate the complex and fluctuating ambient light encountered in typical operating environments, providing a stringent test for the signal extraction capabilities of the digital lock-in amplifier algorithm. The rationale behind this design choice was to assess the system's ability to isolate the desired modulated signal even when subjected to significant and spectrally diverse interference, mirroring potential real-world applications where ambient light conditions are not stable or easily controlled.

2.3. Experimental procedure

Hardware system setup involved connecting the Arduino Uno to a computer via a USB cable for programming and power supply, and assembling the LED driver circuit on the breadboard, where the LED was connected to the digital output pin of the Arduino Uno (pin 9 in the code) via a current limiting resistor; the FIT0031 optical sensor was also connected to the breadboard, ensuring that its VCC and GND pins were connected to the Arduino's power supply (5V and GND, respectively) and its analog output (AOUT) pin was connected to the analog input pin of the Arduino Uno (pin A0 in the code).

Optical signal modulation was achieved by programming the Arduino Uno to generate a PWM signal with a frequency of 1000 Hz and a duty cycle of 50% on the specified digital output pin, pin 9, which periodically turned the LED on and off, resulting in modulated light emission at a specified frequency, and the FIT0031 optical sensor was positioned to detect the light emitted by the LED.

Synchronous demodulation process was implemented on Arduino Uno where the analog voltage signal of the FIT0031 optical sensor, representing the detected light intensity and noise, was continuously sampled by the analog-to-digital converter (ADC) of the Arduino Uno at a sampling rate of 10 kHz, and the digital lock-in amplifier algorithm performed the following steps: a first-order low-pass filter was applied to the sampled signal to estimate and subtract any DC offset caused by ambient light or low-frequency drift, which is the DC offset removal; a digital sine wave with a

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frequency that exactly matched the LED modulation frequency of 1000 Hz was generated in the Arduino and used as a synchronous reference signal, which is the reference signal generation; the AC component of the sensor signal, after removing the DC offset, was multiplied at each sampling point by a digitally generated synchronous reference signal, which is the mixing; a moving average filter with a window size of 50 samples was applied to the mixed signal to extract the low-frequency components representing the amplitude of the modulated optical signal and to attenuate the high-frequency noise components, which is the low-pass filtering; finally, the final filtered signal value was transferred from the Arduino Uno to the connected computer via the serial port at a baud rate of 115200 bps for subsequent analysis and visualization, which is the data output.

3. Result

To evaluate the performance of the Arduino-based digital lock-in amplifier under real and dynamic environmental noise, the experimental setup was placed in front of a computer screen where video content was being played. The setup is designed to simulate complex ambient light noise with different intensity and frequency components. The LED emits a target light signal at a specific modulation frequency of 1000Hz, which is finally detected by the FIT0031 optical sensor and uploaded to the computer.

Due to the limited static Random Access Memory (SRAM) of the Arduino Uno, directly acquiring and storing a large number of samples for batch processing is not possible. The implementation is suitable for processing sensor signal samples one by one in the loop () function and immediately mixing, filtering, and serially transmitting the results. This approach effectively circumvents memory constraints and allows continuous monitoring.

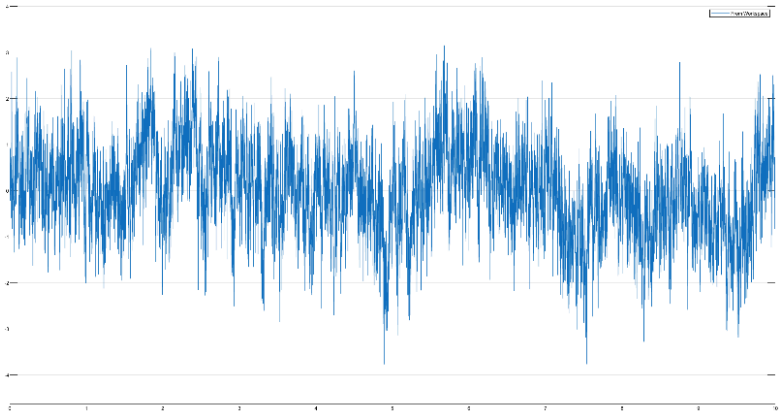

Figure 1: Raw sensor signal captured (photo/picture credit: original)

Figure 1 presents a representative segment of the raw sensor signal acquired while the experimental setup was positioned in front of a screen displaying video content. The captured waveform reveals a highly irregular and dynamic pattern, characterized by substantial fluctuations in amplitude across the recorded time interval. This complex and fluctuating noise, directly resulting from the rapidly changing light intensity and spectral components emanating from the video playback, effectively obscures the underlying sinusoidal signal originating from the LED modulated at 1000Hz. Visual inspection of this raw signal makes it exceedingly difficult, if not impossible, to discern the presence or characteristics of the target 1000Hz signal due to the overwhelming amplitude and unpredictable nature of the interference introduced by the video screen. The broadband nature of the noise suggests the presence of numerous frequency components beyond the

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target modulation frequency, further complicating the direct extraction of the desired signal from this unprocessed data. This visual representation underscores the necessity for sophisticated signal processing techniques, such as the implemented digital lock-in amplifier, to isolate the weak modulated signal from such a challenging noise environment.

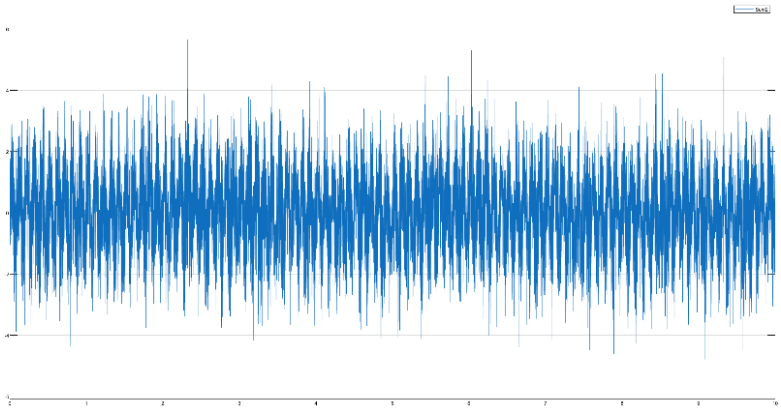

Figure 2: Output signal (photo/picture credit: original)

Figure 2 illustrates the processed output signal after the digital lock-in amplifier algorithm was applied to the noisy input captured from the optical sensor. In contrast to the highly erratic and obscured waveform of the raw sensor signal (as seen in Figure 1), this processed signal exhibits a distinguishable sinusoidal waveform oscillating at the specific modulation frequency of 1000 Hz. The emergence of this clean sinusoidal pattern signifies a substantial reduction in the broadband noise that dominated the raw data. The digital lock-in amplifier, through its synchronous detection and filtering mechanisms, has effectively attenuated the uncorrelated noise components originating from the dynamic video screen, allowing the underlying signal, which is temporally correlated with the 1000Hz reference, to become prominent. The relatively smooth and consistent amplitude of the recovered 1000Hz sine wave suggests a significant improvement in the signal-to-noise ratio, demonstrating the algorithm's capability to selectively extract the desired modulated signal even in the presence of strong and complex interference. This visual transformation from a noise-dominated signal to a clear sinusoidal waveform at the target frequency provides compelling evidence for the efficacy of the implemented digital lock-in amplifier in recovering weak modulated optical signals in noisy environments.

Experimental observations exhibit noticeable delays in the system, which may be due to real-time processing and serial data transfer by Arduino. For simple detection signals work can be done, but for applications that require tight synchronization, this delay is a factor to consider.

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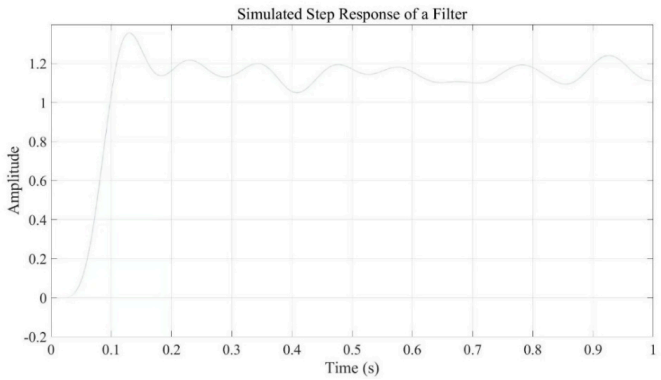

Figure 3: Spectrum of the simulink (photo/picture credit: original)

Figure 3 displays the frequency spectrum of the processed output signal from the Simulink simulation of the digital lock-in amplifier. The x-axis represents frequency, measured in Hertz (Hz), spanning a range relevant to the simulation parameters. The y-axis represents the magnitude of the signal's frequency components, typically displayed in a linear scale, indicating the strength of each frequency component present in the output signal. The most prominent feature of this spectrum is a sharp and distinct peak located precisely at the modulation frequency. The horizontal position of this peak directly corresponds to the frequency of the modulated signal that the lock-in amplifier is designed to detect and isolate. The height of this peak signifies the relative amplitude or power of the recovered signal at the modulation frequency after the noise reduction process. Notably, the spectral content at frequencies other than the modulation frequency exhibits significantly lower magnitudes, indicating substantial attenuation of the noise components. This demonstrates the effectiveness of the digital lock-in amplifier in selectively suppressing noise across a broad range of frequencies while preferentially amplifying the signal of interest. The narrowness of the peak at the modulation frequency reflects the good frequency selectivity of the implemented algorithm, implying that it can effectively discriminate between the desired signal and noise components that are spectrally separated. These spectral characteristics, obtained under controlled simulation conditions, provide a clear validation of the lock-in amplifier's noise suppression capabilities and its ability to isolate the weak modulated signal in the frequency domain, complementing the time-domain observations from the physical Arduino implementation.

4. Discussion

The results of this study demonstrate the practicality and effectiveness of a low-cost digital lock-in amplifier, implemented using Arduino Uno, for a weak modulated optical signal doped from a noisy environment simulated by a playback video screen. The 1000 Hz LED signal was successfully retrieved from the initial sensor readings in noise (Figure 1, 2), highlighting the noise cancellation capability of the implemented synchronous detection method [4].

In Simulink simulations, the observed reduction of the noise component over a wide frequency range (Figure 3), together with the persistent prominence of peaks at the modulation frequency, further supports the basic concept of lock-in amplification: selectively enhancing signals synchronized to the reference frequency while suppressing irrelevant noise [4]. Frequency domain analysis reflects the improvement over time seen in the experimental results, with 1000 Hz sinusoidal signals becoming distinguishable after processing.

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The limited memory (SRAM) on the Arduino Uno motherboard requires a sequential, sample-by-sample processing strategy. While this effectively manages memory constraints, it does introduce significant time delays in the system, as our experimental observations show. For time-critical applications, the tradeoff between memory efficiency and responsiveness is a key factor to consider [5]. Prior work has deeply investigated the inherent limitations of microcontroller-based data acquisition systems, in particular the maximum sampling speed and computational power involving complex algorithms [6]. Additionally, the impact of serial communication interfaces, such as those used by the Arduino, on introducing delays and limiting the overall data throughput in real-time applications has been well documented [7]. For simpler detection tasks, the current setup performs well when immediate feedback is not Paramount. However, this product is not suitable for real-time applications that require high feedback efficiency.

Simulation of environmental noise using a playback video screen produced a demanding but effective test scenario. The wide bandwidth and changing nature of the fluctuating light from the screen effectively model the complex background interference encountered in various real-world environments, such as outdoor sensing or industrial locations with fluctuating light sources [8]. The successful isolation of modulated LED signals under these conditions underlines the resilience of the digital lock-in amplifier approach.

The experimental results obtained in the actual Arduino environment are consistent with the control simulation performed in Simulink, which provides strong supporting evidence for the effectiveness of the implemented algorithm [9].

The low cost and ease of use of the Arduino platform make this digital lock-in amplifier a promising educational tool, requiring only the basic code of signal processing and the principles of instrumentation [10]. Furthermore, with possible improvements and the use of more powerful microcontrollers, this approach can be adapted to application areas where cost is not prohibitive, such as environmental monitoring in the community or basic scientific exploration, where high-performance, expensive commercial lock-in amplifiers may be impractical.

5. Conclusion

This study successfully demonstrated a cost-effective digital lock-in amplifier for detecting weak optical signals in noisy environments, which was implemented on an Arduino Uno and validated by Simulink simulations. The Arduino-based system effectively extracts 1000 Hz modulated LED signals from heavily noise-contaminated sensor data, demonstrating the principle of selectively amplifying synchronization signals and suppressing noise even with a basic microcontroller.

The study highlighted the limitations of the Arduino Uno in terms of memory and processing, resulting in system delays due to the need for sample-by-sample processing. While suitable for educational purposes and basic detection, this delay hinders real-time applications. Future work should explore more powerful hardware platforms or DSPS to improve responsiveness to time-critical tasks.

The use of a dynamic video screen as a photorealistic noise source demonstrates the potential of the system in challenging ambient light conditions, relevant for cost-sensitive applications such as basic environmental monitoring and educational tools. The consistency of the experimental and simulation results verifies the effectiveness of the proposed algorithm in weak signal recovery.

In conclusion, this study establishes Arduino Uno as a viable platform to implement digital locked-in amplification for low-cost detection of weak light signals. While acknowledging its limitations, this study provides a basic solution for the selection of educational tools and basic sensing. Future efforts should focus on optimizing algorithms and exploring more powerful

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hardware to address latency issues and expand applicability to real-time and high-performance sensing.

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