**Implementing an Intermittent Computing System for an Autonomous Ocean Analyzer Prototype**

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| A Project Report Presented to  The Faculty of the College of Engineering |
| San Jose State University In Partial Fulfillment Of the Requirements for the Degree  **Master of Science in Computer Engineering**  **Master of Science in Software Engineering** |

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| 12/2023 |

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ABSTRACT

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By Virag Bhanderi, Milan Dudhtara, Moxank Patel

This study introduces a novel power management system for the Programming Flow Injection Ocean Nutrient Analyzer (pFIONA), an instrument for comprehensive chemical analysis in oceanic environments. Recognizing the importance of power efficiency for such autonomous systems, our proposal incorporates intermittent computing strategies into the existing framework, intending to construct a dependable, self-sufficient system capable of effective operation under various marine conditions. To further strengthen the device's self-reliance, we plan to integrate intelligent decision-making capacities within its power management system, designed to predict and adjust accurately to changing weather conditions, thereby significantly enhancing operational efficiency. Leveraging state-of-the-art technologies and methodologies, we expect to achieve several key outcomes: a) developing a hull design incorporating a power management circuit in tandem with a solar panel, ensuring a well-integrated and efficient system, b) designing an autonomous power system that eliminates the need for external power sources, thereby augmenting the device's adaptability in diverse marine settings, and c) incorporating intermittent computing strategies and renewable energy generators, thus to extend the system's operational duration considerably. This work intends to facilitate the transformation of pFIONA into a completely autonomous system, thereby enhancing its functionality in conducting complex marine chemical analyses.

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*Abstract* — This study introduces a novel power management system for the Programming Flow Injection Ocean Nutrient Analyzer (pFIONA), an instrument for comprehensive chemical analysis in oceanic environments. Recognizing the importance of power efficiency for such autonomous systems, our proposal incorporates intermittent computing strategies into the existing framework, intending to construct a dependable, self-sufficient system capable of effective operation under various marine conditions. To further strengthen the device's self-reliance, we plan to integrate intelligent decision-making capacities within its power management system, designed to predict and adjust accurately to changing weather conditions, thereby significantly enhancing operational efficiency. Leveraging state-of-the-art technologies and methodologies, we expect to achieve several key outcomes: a) developing a hull design incorporating a power management circuit in tandem with a solar panel, ensuring a well-integrated and efficient system, b) designing an autonomous power system that eliminates the need for external power sources, thereby augmenting the device's adaptability in diverse marine settings, and c) incorporating intermittent computing strategies and renewable energy generators, thus to extend the system's operational duration considerably. This work intends to facilitate the transformation of pFIONA into a completely autonomous system, thereby enhancing its functionality in conducting complex marine chemical analyses.

*Index Terms* — *Intermittent Computing, Power Management, DICE Technique, Dynamic Voltage Frequency Scaling (DVFS), Ocean Nutrient Analyzer, Renewable Energy Generators, Self-Sustaining Systems.*

# INTRODUCTION

T

he complex dynamics inherent in marine ecosystems require a sophisticated understanding, achievable through advanced scientific instrumentation [1]. Among the tools at our disposal, analyzers such as the Nitrogen Nutrient Analyzer [2] and the Automatic Colorimetric Analyzer [3] have been specifically designed to dissect the intricate mix of compounds found within seawater. These analyzers serve multi-faceted roles: monitoring water quality, contributing to climatological studies, evaluating ecosystem health, assisting in scientific research and conservation, and facilitating a wide range of commercial applications [2],[3]. These oceanic analyzers are essential for broadening our comprehension of marine environments, formulating effective conservation strategies, and promoting the sustainable management of marine resources. The Programmable Flow Injection Ocean Nutrient Analyzer (pFIONA) [4] is one such system that was developed while accounting for the cost factor. The system does all the functionality that the analyzers mentioned above do. Still, the system needs an external power supply, so this research aims to leverage solar energy and incorporate intermittent computing with other state-of-the-art techniques to bolster the system's robustness and make it self-reliant.

The Programmable Flow Injection Ocean Nutrient Analyzer (pFIONA) is a key innovation in oceanic nutrient analysis. Through the leverage of open-source technologies, pFIONA presents a substantial enhancement to the accessibility, reproducibility, and scalability of marine data. The instrument integrates established Programmable Flow Injection (pFI) methodologies [4], [5], enabling meticulous analysis of phosphate and silicate in seawater – a capability that is particularly suited for field deployment. Oceanic analyzers such as pFIONA, entrusted with the crucial task of identifying and analyzing marine chemical compositions, require the capacity to operate over extended periods with minimal power consumption [5]. These instruments encompass multiple power-intensive components, including water-pumping motors and a spectrometer, underscoring the need for a power management strategy. pFIONA currently needs an external power supply. To eliminate this, a simplistic approach is to install a battery capacity with a large degree that is not viable due to the resultant escalation in the device's size.

To address this research endeavor, we propose developing a sophisticated power management system capable of making intelligent decisions based on sunlight conditions. A visual representation of our design concept is presented in Figure 1, which illustrates the buoy's hull housing the power management system. This buoy is firmly anchored by two supports and is equipped with an array of solar panels, ensuring autonomous power generation. Additionally, the buoy incorporates a water pump house, schematically depicted in Figure 2, which serves as the second layer of protection for pFIONA, as it facilitates the exclusion of undesired objects from the system.

Diagram of a solar panel

Description automatically generated

Fig. 1. Conceptual Design of the hull along with the solar panel.

A diagram of a device

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Fig 2. Conceptual design of the water pump

Considering these considerations, we propose reducing power consumption by integrating intermittent computing. This strategy allows the device to intermittently pause and resume operation, achieving a dual objective – power conservation and increased robustness against system failures [4]. Instead of resorting to a cost-intensive expansion of the battery capacity, the deployment of intermittent computing provides a route to minimize power requirements without a proportional increase in expenditure.

We propose adopting the DICE technique for checkpointing – an efficient algorithm designed to conserve energy by updating only crucial changes, thus eliminating the necessity for extensive checkpointing [7]. Our design proposition also incorporates a smart, autonomous power management system to prolong the device's operational lifespan [8]. We recommend applying Dynamic Voltage and Frequency Scaling (DVFS) for further power usage optimization. This approach allows the device to operate in a low-power mode, further attenuating power consumption [9].

To summarize, our project is expected to yield the following significant contributions:

1. We aim to develop a novel hull design, effectively a buoy, which integrates a power management circuit with a solar panel, facilitating an efficient and self-contained system. The buoy's internal compartment will be filled with dense cement to adjust the center of gravity and ensure stability. Anchoring strategies will be implemented to stabilize the buoy's position within a marine environment.
2. Our second objective involves designing an autonomous power system that eliminates the dependency on external power sources. This feature enhances the device's adaptability across a wide array of marine settings. A foldable solar panel attached to the buoy will harness solar energy, establishing a renewable power source.
3. We propose incorporating intermittent computing strategies with renewable energy sources to significantly extend the system's operational duration. This approach will enable the Programmable Flow Injection Ocean Nutrient Analyzer (pFIONA) to pause and resume operation as needed, conserving power without compromising its function. Dynamic voltage and frequency scaling (DVFS) will enable the system to operate in a low-power mode.

This paper outlines the architectural blueprint for our proposed power management system and the application of intermittent computing to navigate these power-related challenges. The report is segmented as follows: Section II addresses the Problem Statement, Section III details the Methods, Section IV delves into the Evaluation, Section V presents the Results, Section VI discusses these findings, and Section VII lists the References.

# Background and related work

## Metrics

We will use several critical metrics to evaluate the proposed system's performance. Firstly, the discharge-to-charge ratio will be analyzed, serving as an indicator of the system's longevity. A lower ratio would be more desirable, denoting that the system can function for extended durations on a single charge cycle [10]. Secondly, we plan to compare the system's runtime and power consumption (measured in joules). This juxtaposition will enable us to evaluate the effectiveness of intermittent computing in improving the system's overall efficiency. According to standard metrics, an ideal system should demonstrate a prolonged runtime with minimal power consumption [6].

Thirdly, we propose to measure the volume of data written during checkpointing. This metric will help ascertain the efficiency of intermittent computing. Concurrently, the time taken for each checkpointing process will be monitored to gauge the system's operational speed during these critical periods. Another metric pertinent to Intermittent Computing would be the count of checkpoints during system operation [7]. This count could provide insights into the frequency of safe system state preservation, essential for recovering from unexpected power losses. Lastly, to gauge system reliability, we plan to calculate the ratio of successful operations to the total number of operations conducted. This ratio will quantitatively measure system dependability, indicating the likelihood of successful operation completion under given conditions.

## Baseline Systems

This section of the manuscript presents a meticulous examination of the state diagram outlining the operations integral to the Programmable Flow Injection Ocean Nutrient Analyzer (pFIONA). This rigorous analysis offers valuable insights into the complex mechanisms underpinning the instrument's functionality. Further, it expounds upon the architectural specifics of the circuit design intended for solar energy generation, elucidating the integral role of renewable energy within the system's operational framework. Lastly, delineating a high-level state diagram for the proposed system briefly outlines the interactions and functionalities of integrated components, thereby facilitating a comprehensive understanding of the system's architectural and operational intricacies.

Fig*.* 2. State Diagram for pFIONA

The schematics in Design of Solar Harvesting Circuit for Battery less Embedded System presented by R.A. Kjellby [10] represent a solar harvesting system incorporating a Maximum Power Point Tracking (MPPT) algorithm. This MPPT algorithm functions by discerning the optimal angle to position solar panels to maximize power generation. Such a strategy serves as a significant reference for our proposed system. Our system strives to augment the efficiency of this concept by not only tracking environmental conditions - but specifically sunlight also - and predicting future power generation based on these tracked conditions. This predictive analysis then informs the moderation of device power consumption, allowing the system to adapt its power utilization in response to anticipated power generation trends. By integrating these processes, our system aims to elevate the proficiency and adaptability of solar power harvesting technologies.

This state machine, depicted in Fig 3 is designed to control the operation of a device by transitioning between various states. Each state represents a specific action or operation. The state machine continuously monitors events and timers, determines the next state based on the current state, and initiates parallel threads to perform the necessary tasks. The outcome of each state execution determines the next state, with an error state serving as a fallback option. If an unknown condition is encountered, an error is triggered. The state machine updates the current state, facilitating the transition from one state to another.

A diagram of a battery

Description automatically generated with low confidence

Fig. 3. State Diagram for proposed power system

The proposed electrical power system has several operational modes that the system may transition between based on circumstances and user commands, which are depicted through the state diagram in Appendix Figure 3 and the ASM chart in Fig 4. The primary modes of operation are charge mode (also referred to as idle mode), high power mode, low power mode, and a buffer state. Initially, the system defaults to idle or charge mode, wherein the principal objective is accumulating energy in the battery. The transition from this initial mode to high power mode occurs once the battery charge level meets or exceeds a predetermined Upper Defined Threshold (UThres). In the high-power mode, the system provides power to the circuit and operates at its full capacity.

Two circumstances can trigger a shift from high-power mode to low-power mode. The first is an explicit command from the user, and the second is when the battery charge level falls below a set Lower Defined Threshold (LThres). Once in low power mode, the system may revert to high power through another user command or when the battery charge escalates above the UThres.

A critical feature of this power system is its ability to enter a buffer state when the battery charge decreases below an extremely low threshold (XThres) during low power mode. The buffer state is designed to wait for a signal from the circuit, indicating that the device has successfully preserved its form. Upon receiving this signal, the power system returns to its initial idle state. The proposed power system presents a flexible and adaptive operation modality that optimizes performance based on user commands and battery charge level thresholds. These strategic modes of operation aim to manage power consumption efficiently and ensure the preservation of the device state during critical battery levels.

A diagram of a battery

Description automatically generated with medium confidence

Fig. 4. ASM chart for power system

## Related Work

Recent advances have highlighted the importance of checkpointing and memory management in intermittent computing. In particular, storing the processor's content and the system state in non-volatile memory is critical to checkpointing. This task is relatively inexpensive given the high cost of writing to non-volatile memory. A pioneering approach presented by Bhattacharya et al. aims to minimize the number of operations/checkpoints achieved by renaming the non-volatile memory address. This work reduced checkpointing by 20%, thus significantly cutting power consumption by nearly 80% [7].

The efficient division of tasks across multicore processors can significantly curtail power consumption from a hardware perspective. A coordinated hardware and software approach proposed by Henkel suggests allocating tasks to the core processor based on their load, which results in a higher utilization rate [8]. This strategy achieved power savings of up to 94% for a specific configuration. In addition to methods to reduce power consumption, considerable efforts have been directed toward developing energy-harvesting solutions for wireless IoT devices and embedded systems. Notably, the prototype power management system designed by Kjellby et al. operates exclusively on energy harvested from a small solar panel [10].

A prominent case study in low-powered IoT devices is Chimera, which can instantaneously switch between computing-intensive and passive tasks while retaining multi-year battery life [12]. Chimera's ability to apply the above strategies in a practical context exemplifies the potential of these power-reducing methods in IoT. The methodologies and architectures are tailored to specific systems, precluding their broad application across diverse architectures. As such, they do not lend themselves readily to the unique requirements of the Programmable Flow Injection Ocean Nutrient Analyzer (pFIONA). Consequently, there is a clear necessity for a versatile framework capable of performing critical tasks such as power conservation, intelligent decision-making, and supporting intermittent computing.

## State of Art

Reducing power consumption has been a key research area in IoT technology, with many low-power techniques developed to achieve this goal. However, most of these techniques have focused on reducing the consumption rate alone, as energy consumption is the product of power and time [4]. A more comprehensive approach, which encompasses power and time usage, is required to improve energy efficiency in IoT devices [4]. Efforts to reduce power consumption in IoT devices have spanned software and hardware strategies. On the software side, minimizing the number of computations and optimizing software have been identified as key means to decrease power consumption. In terms of hardware, redesigning hardware to enhance power efficiency presents a viable solution [9].

Intermittent computing has emerged as a well-known technique for reducing power consumption on the software side [4]. The goal of intermittent computing is to allow execution to resume from when it was halted, thus negating the need to reboot the entire process. This reduces power consumption and bolsters the system's fault tolerance. A key development in intermittent computing is Differential Checkpointing for Intermittent Computation Execution (DICE), which offers a software-based solution to diminish the overhead of state checkpointing faced by embedded devices operating on ambient energy [7]. DICE employs differential checkpointing, storing only the changes made to the system state since the last checkpoint. This strategy reduces the energy cost and execution time of checkpointing [8].

Dynamic Voltage and Frequency Scaling (DVFS) is a key power and thermal management strategy for modern computing systems. Its prominence has grown over recent years due to its unique ability to minimize energy consumption while avoiding major performance trade-offs [16]. The state-of-the-art in DVFS extends beyond its traditional application in CPUs, embedded systems, and large-scale data centers [17], [18]. Advancements in machine learning and predictive modeling have bolstered the capabilities of DVFS, enabling it to accurately discern the optimal voltage and frequency settings [16]. Such developments are crucial in managing power-performance trade-offs and fortifying system reliability across various workloads and thermal conditions.

# System Design

A diagram of a sphere with text

Description automatically generated

Fig 5. The design is for keeping the Inlet pipe on the surface.

# Evaluation Methodology

## Evaluation Metrics

We establish distinct metrics to gauge performance and reliability in assessing the system's efficiency, specifically the 'pFiona' component. These metrics are as follows:

1. **Average Daily Cycles**: This metric calculates the average number of operational cycles' pFiona' can complete within 24 hours. It indicates the system's operational efficiency under varying environmental conditions and power availability scenarios.
2. **System Availability**: Defined as the proportion of time 'pFiona' remains operational over a fixed 12-hour window, this metric assesses the system's uptime and readiness. It reflects the system's ability to maintain continuous operation, which is crucial for high-availability applications.
3. **Reliability Factor**: This metric is quantified by the total number of instances where 'pFiona' is forced to restart its operations from the beginning despite the presence of a checkpoint. The summation of these events measures the system's robustness against interruptions and capacity to recover from unforeseen disruptions.

# Conclusion

This work implements an intermittent computing system for the ocean analyzer pFIONA. We deliver a complete analyzer package through our carefully designed buoy, power management system, intermittent computing framework, and user interface. Our system can provide high reliability and sustainability in complex marine environments. Our upgraded web-based UI also improves accessibility and ease of use. These advancements collectively make pFIONA a more practical and effective real-time ocean nutrient monitoring tool.

# Acknowledgment

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# Appendix 1

A diagram of a solar panel

Description automatically generated

Fig A.1 Block Diagram of the proposed system.

A diagram of a state

Description automatically generated

Fig A.2 State diagram for pFiona

A picture containing text, diagram, plan, technical drawing

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Fig A.3 Decision Tree to determine whether to Run pFIONA

A screenshot of a computer

Description automatically generated

A screenshot of a computer

Description automatically generated

Fig A.4 Snapshots of User Interface.

A diagram of a company

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Fig A.5 Decision tree for Nano Board

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