Implementing an Intermittent Computing System for an Autonomous Ocean Analyzer Prototype

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ABSTRACT

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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.

Acknowledgments

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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.

I. Introduction

The 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 (pFiona) 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.

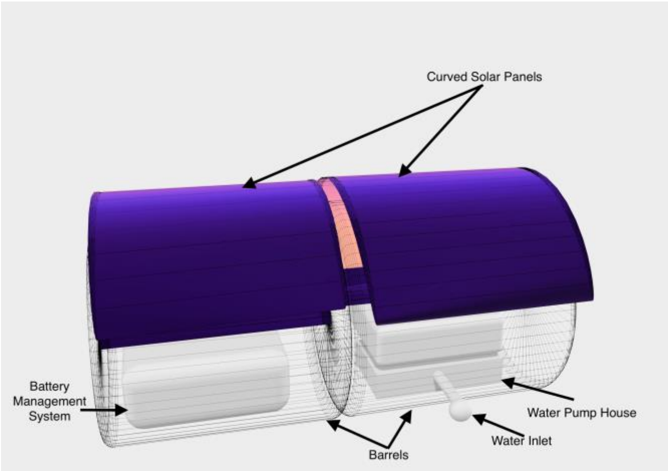

Fig. 1. Conceptual Design of the hull along with the solar panel.

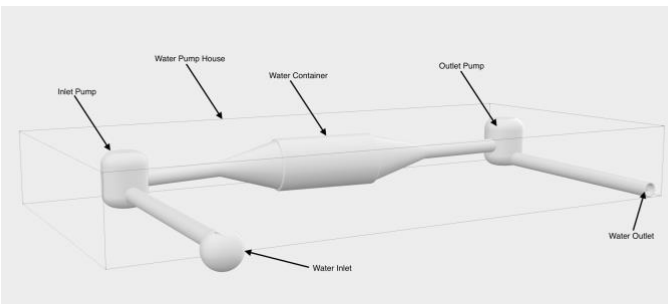

Fig 2. Conceptual design of the water pump.

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:

- Solar-Powered Buoy Design: In developing a solar-powered buoy, our design focuses on incorporating solar panels on the exterior of an encapsulation. This encapsulation houses critical internal modules for power management, seawater collection and disposal, and the analyzer. The primary objective of this design is to offer robust protection against the challenging marine environment. The strategic placement of solar panels ensures optimal energy harvesting. At the same time, the internal compartmentalization safeguards the system's critical components from the harsh sea conditions.
- Power Management System: Our power management system is meticulously engineered to augment the sustainability of the analyzer. This is achieved through a tripartite approach: firstly, by optimizing the energy harvesting efficiency from the solar panels; secondly, by dynamically scheduling the execution cycles of the analyzer to align with power availability; and thirdly, by incorporating Dynamic Voltage and Frequency Scaling (DVFS). The DVFS technique significantly reduces the power usage of the controller board, thereby enhancing the system's overall energy efficiency.
- Intermittent Computing Framework: Given the intermittent nature of energy harvesting, particularly in solar-powered systems, we have integrated a high-reliability framework into our design. This framework is based on a state-machine approach complemented by a coarse-grained checkpointing methodology. Combining these techniques ensures the system maintains its operational integrity and data consistency, even in fluctuating energy inputs. This design consideration is vital for the sustained reliability of the system in environments with variable energy availability.
- Upgraded User Interface: Building upon the original UI for pFIONA, we have developed an advanced web-based user interface utilizing the Django framework. This upgraded UI offers several enhancements over its predecessor. It provides more comprehensive control options for power management, an expanded range of tools and options for system operation, and an improved visual layout and design. Furthermore, using the Django framework brings about better accessibility and user interaction, making the system more user-friendly and efficient. These improvements in the UI not only enhance the user experience but also contribute to more effective system management and monitoring.

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.

II. Background and Related Work

A. 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.

B. 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.

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.

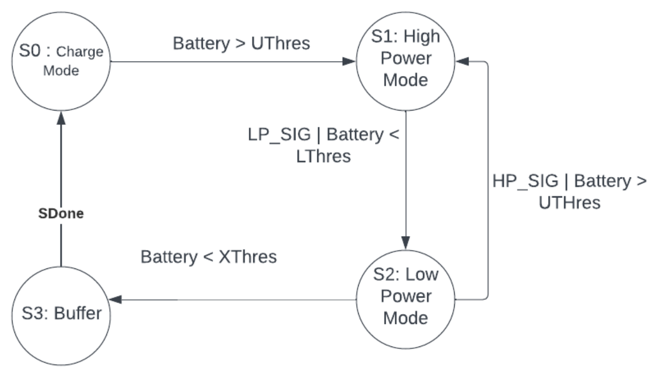

Fig. 3. State Diagram for the proposed power system.

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.

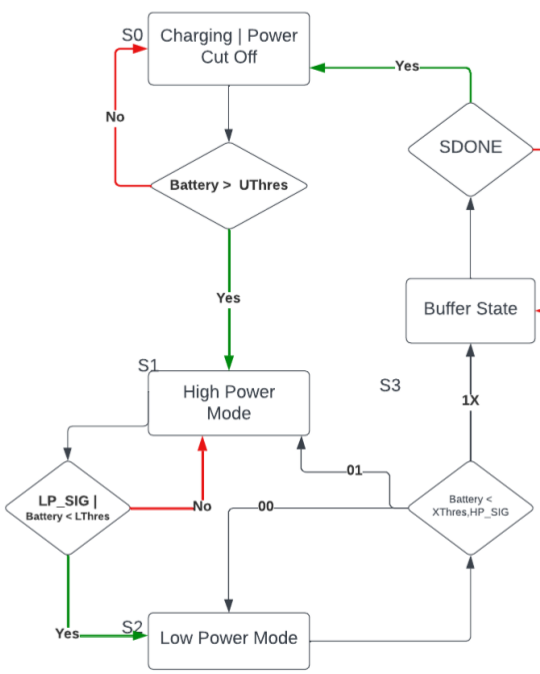

Fig. 4. ASM chart for power system.

C. 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.

D. 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.

III. System Design

This section elaborates on the intricate system design, incorporating four principal elements: the power management system, intermittent computing, Dynamic Voltage and Frequency Scaling (DVFS), and an advanced user interface for pFiona. These components' harmonious integration and effective operation are crucial for optimizing the system's overall efficiency and performance. Each element plays a vital role in enhancing the system's functionality, thereby contributing significantly to the robustness and effectiveness of the system.

A. Buoy Design

The system's architecture is characterized by a modular design approach, strategically dividing the power management system and the pFiona unit into distinct, barrel-shaped modules. This modularization significantly enhances the system's flexibility and robustness, allowing it to cater to various operational requirements adeptly.

A notable aspect of this design is integrating the pFiona unit with a water pump house, as depicted in Figures 2 and 5. This integration consolidates essential components into a single, efficiently managed unit. This combination is pivotal in streamlining operations and ensuring critical elements are housed within a cohesive structure.

Concerning physical security and stability, each barrel is reinforced using steel ropes, providing a robust anchoring mechanism. The interiors of the barrels are filled with polyurethane foam, offering both cushioning, and added protection against external elements. This design consideration is crucial for safeguarding the system against physical shocks, vibrations, and other environmental stresses, thereby maintaining the integrity and functionality of the components housed within.

The barrels' design is ingeniously inspired by the principles of roly-poly toys, ensuring that they maintain an upright position by positioning the center of gravity at the bottom. This feature is especially advantageous in aquatic environments where stability is paramount. The barrels are adept at automatically returning to their original position regardless of movement or orientation, thus ensuring continuous and uninterrupted operation.

Furthermore, each barrel designated for pFiona is equipped with compartments for storing necessary reagents. This thoughtful design ensures that all required materials for the operation of pFiona are readily accessible, facilitating efficient and timely processing.

The buoy design, encapsulating the power management system, the analyzer, and the water collection and disposal system, employs a cylindrical shape to provide high structural strength. This shape not only contributes to the system's physical robustness but also enhances its steadiness in water environments. The cylindrical design aids in maintaining the optimal orientation of the solar panels, ensuring consistent energy harvesting. The modular configuration within the buoy provides isolation between systems, with foam filling the gaps between modules to enhance resistance to water, impact, heat, and electric shocks.

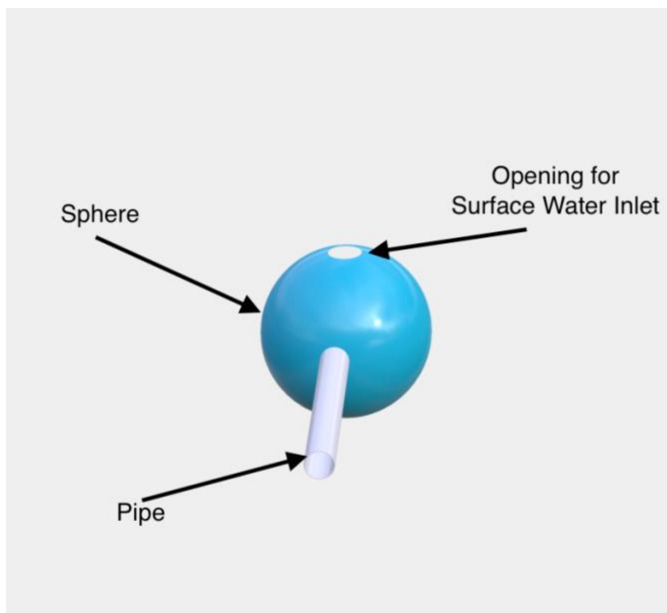

Fig. 5. Inlet design for water pump house.

In Figure 5, the inlet design for our ocean-based system is depicted, featuring a spherical structure with dual openings: a direct opening and another connected to a pipe leading to the water pump house. This sphere is internally equipped with a filter to exclude extraterrestrial substances, ensuring only desired ocean water is processed. The design allows the sphere to float on the ocean surface, as it is hollow, catering to pFiona's requirement for water from the ocean surface bed. The water entry point is strategically placed at the top of the sphere, optimizing water intake while minimizing the entry of unwanted materials, showcasing an efficient and environmentally attuned design.

In summary, the buoy design is a sophisticated blend of structural integrity, environmental adaptability, and operational efficiency. Its modular architecture not only safeguards the internal components but also ensures consistent performance under diverse conditions, making it an indispensable part of the system.

B. Power Management System

The power management system, illustrated in Fig. 6, forms the foundational architecture of the design, incorporating several essential components that are vital for the system's efficiency and operational effectiveness. Central to this system are solar panels, which serve as the primary mechanism for generating electrical energy through solar power harnessing. Complementary to this are the batteries, crucial for storing the electrical energy derived from the solar panels, thereby guaranteeing a steady supply of energy.

Integral to the power management system is the Solar Charge Controller, a component that is key in managing the charging process of the batteries. Its function is to prevent both overcharging and deep discharge, thus preserving battery health and efficiency. This controller is available in two types: Maximum Power Point Tracking (MPPT) and Pulse Width Modulation (PWM). The MPPT variant, suitable for larger systems, regulates voltage by simultaneously increasing current and decreasing voltage. Conversely, the PWM variant, ideal for smaller configurations, moderates excess voltage while maintaining a consistent current level.

The Nano Board stands as the central control unit within this system. Its role is to monitor a range of environmental parameters and execute decisions based on a predefined decision tree algorithm. This board is crucial in managing the dynamic responses of the system to fluctuating environmental conditions.

An additional component is the Light-Dependent Resistor (LDR) Sensor. This sensor is tasked with measuring ambient light intensity, providing critical data to the Nano Board for informed decision-making. Moreover, the system includes relays and a voltage converter, both essential in maintaining the correct voltage levels and ensuring efficient power distribution throughout the system.

The Nano Board is entrusted with two fundamental responsibilities. Its first responsibility, Parameter Monitoring, involves the continuous assessment of environmental conditions, encompassing parameters such as light intensity, battery charge rate, and battery charge level. This monitoring is imperative for the adaptive functioning of the system in response to environmental changes.

The second responsibility is the Decision-Making Process. The Nano Board employs an advanced decision tree, as depicted in Appendix Figure 2, to determine the activation of pFiona, a critical component of the system. This decision-making is influenced by multiple factors, including the operational frequency of pFiona, the status of the battery, and prevailing meteorological conditions. This structured decision-making process ensures the optimal operation of pFiona, enhancing the system's overall efficiency and performance.

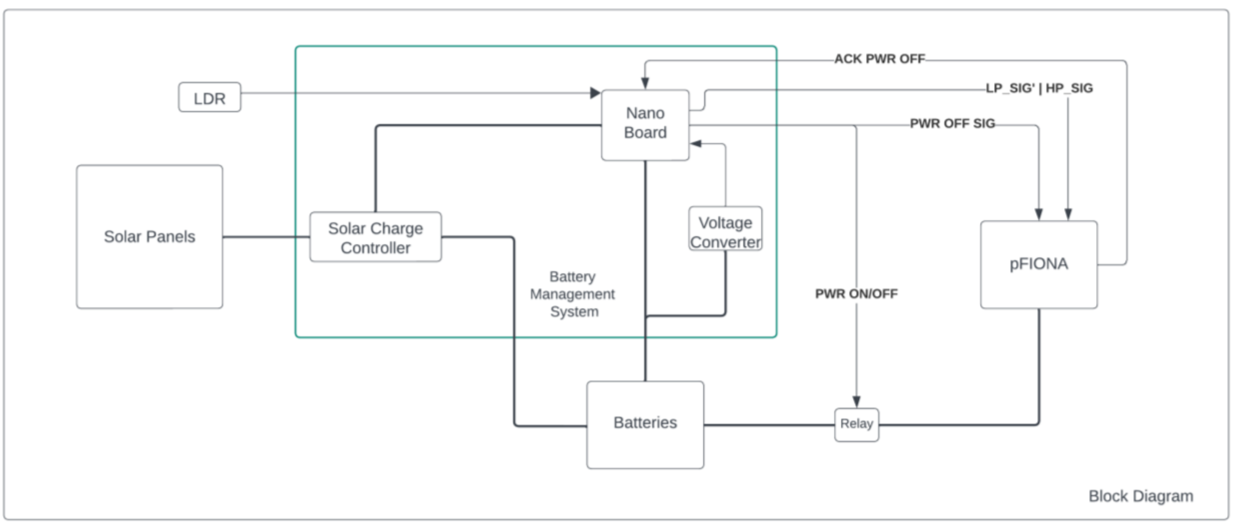

Fig 6. Block Diagram of the proposed system.

The configuration of the power management system is meticulously designed to ensure optimal performance and efficiency. At its core, the system utilizes a dual battery setup, consisting of two 12V batteries connected in series to establish a 24V configuration. This arrangement is crucial not only for achieving a higher voltage output but also for enhancing the system's energy storage capacity, aligning with the operational requirements of the subsequent components.

Further integrating into this setup are the solar charge controller and a voltage stabilizer. The controller, whether it's the MPPT or PWM type, is essential for efficient battery charge management, optimizing the charging process, and preserving battery longevity. The voltage stabilizer plays a pivotal role in ensuring a consistent 24V output from the batteries, effectively compensating for the potential fluctuations from their peak voltage of 29V.

In tandem with this, the solar panels are strategically configured in series, delivering a power output of 200W at 24V. This configuration maximizes the energy harvesting potential, ensuring that the power generated is optimally suited for the system's needs. Additionally, the battery recharge capacity is a critical aspect of the design. Theoretically, each battery's 200W capacity allows for a full recharge in about four hours under optimal solar conditions, a factor that significantly influences the system's energy management and usage planning.

Completing the configuration is the inclusion of a voltage converter, which serves as a crucial interface between the batteries and the Nano Board. It adapts the 0-25V range, typical of the battery output, down to a more manageable 0-5V range, suitable for the Nano Board. This step is imperative to ensure that the Nano Board operates within safe voltage parameters, maintaining the stability and efficiency of the system.

The power management system is thus a critical component that ensures sustained energy supply and efficient system operation. Its intelligent design and sophisticated components work harmoniously to provide a reliable and efficient power solution, essential for the system's long-term sustainability.

C. *Intermittent Computing*

In the operational dynamics of the system, the initiation of pFiona triggers a series of coordinated actions governed by the nano board. Upon activation, the nano board engages a relay switch, which subsequently energizes the voltage stabilizer. This action facilitates the power supply to pFiona, marking the commencement of its operations. A crucial aspect of this process is the communication link between pFiona and the nano board, especially critical when the system encounters a low battery state.

In scenarios where the nano board detects diminished battery levels, it issues a command to pFiona to halt operations and initiate data security protocols. This directive is initiated by a 'power off' signal originating from the Battery Management System (BMS), effectively instructing pFiona to commence shutdown procedures. Following this, pFiona undertakes the task of ensuring all necessary data is securely saved and that all operations are safely concluded. Once these tasks are completed, pFiona transmits an acknowledgment signal back to the nano board. This signal confirms that it is secure to discontinue the power supply, thus facilitating a coordinated and safe shutdown of pFiona. This sequence of signals plays a pivotal role in preserving the system's integrity and preventing any potential data loss.

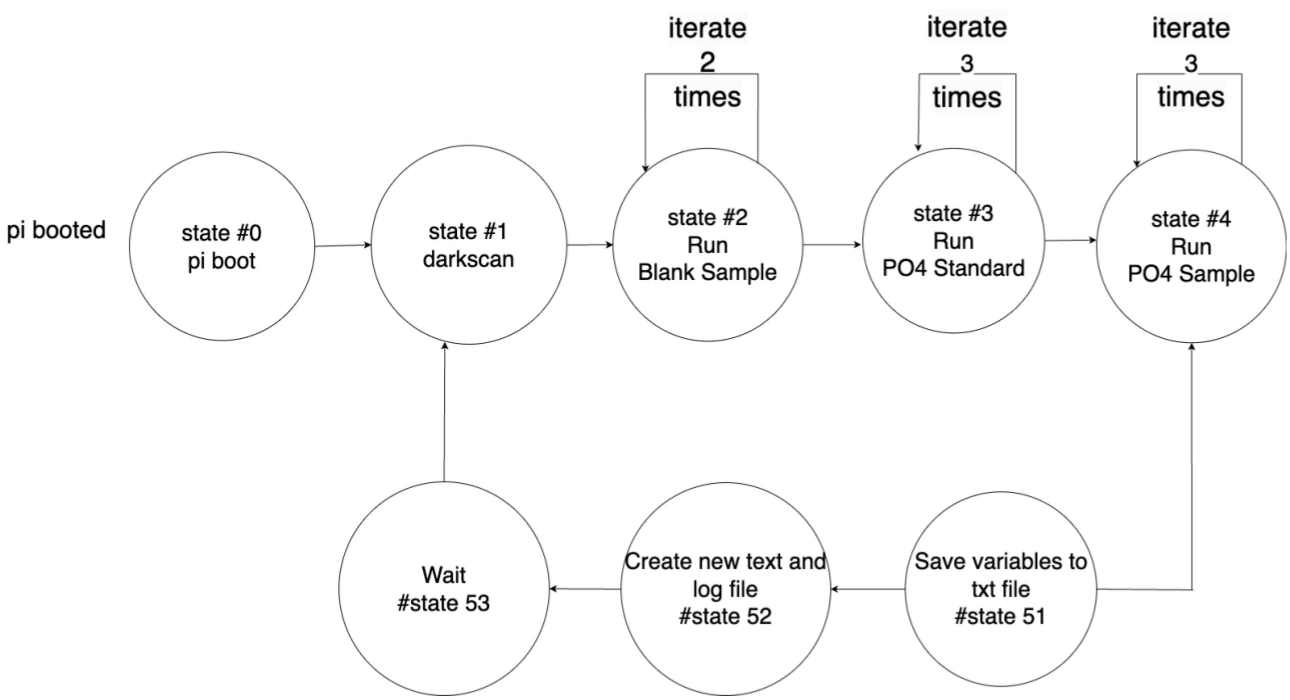

Fig. 7. State diagram for pFiona.

Additionally, the system employs a Raspberry Pi as the control unit for the analyzer. To bolster the system's reliability, a coarse-grained intermittent computing framework is integrated. This framework segments the operational procedures into independent states, as depicted in a high-level state diagram shown in Figure 3. The implementation of this framework allows for the creation of checkpoints for each state from which execution can be restored. The states for which execution cab be resumed are depicted in Fig 7, an abstract state diagram of pFiona. This abstract is partial representation of the entire state diagram for pFiona presented in Appendix Fig A.1.

Consequently, in the event of a power disruption, the system can resume operations from the last completed state, thereby avoiding data corruption. To ensure uninterrupted task execution and progress, the power management system is programmed to prevent the initiation of any state unless the batteries have reached a predetermined minimum charge level. This design consideration is essential for maintaining the continuity and integrity of the analyzer's functions.

In summary, the intermittent computing aspect of our system introduces a robust framework for managing the analyzer's operations. This approach safeguards against data corruption and ensures seamless operations resumption, highlighting the system's reliability and advanced technological design.

D. User Interface

The newly developed user interface (UI) for our system represents a significant advancement over its predecessor, utilizing the Django REST framework to create a sophisticated web-based design. This modern UI operates on a host device, such as a PC, and establishes communication with the analyzer's controller via Wifi. It is engineered to facilitate connections with multiple analyzers and allows seamless switching between them, thereby enhancing user experience and system manageability.

The interface is meticulously organized into various tabs, each offering a multitude of functionalities tailored to specific user needs. The dashboard tab provides a comprehensive overview of pFIONA's operational status and houses the most frequently used controls. For monitoring and debugging purposes, the Log tab presents detailed logs. Historical data amassed from the analyzer is accessible via the Data tab. The Graphs tab, as illustrated in Figure 8 and Figure 9, offers a range of data visualizations, providing users with insightful representations of the collected data. Additionally, the Control tab is equipped with a series of buttons and input fields, enabling users to exert detailed control over the analyzer's status and modify its operational parameters as needed.

Transitioning from the Tkinter framework to Django for the UI development presents numerous advantages, particularly in terms of scalability and performance. Django, being a Model-View-Controller (MVC) framework, offers superior scalability, making it a more suitable choice for systems requiring expansion and enhancement over time. The MVC architecture of Django enables a more structured and modular approach to UI development, facilitating easier maintenance and updates.

Moreover, Django's framework is known for its efficiency in handling latency issues, providing a more responsive user experience compared to Tkinter. This improvement is

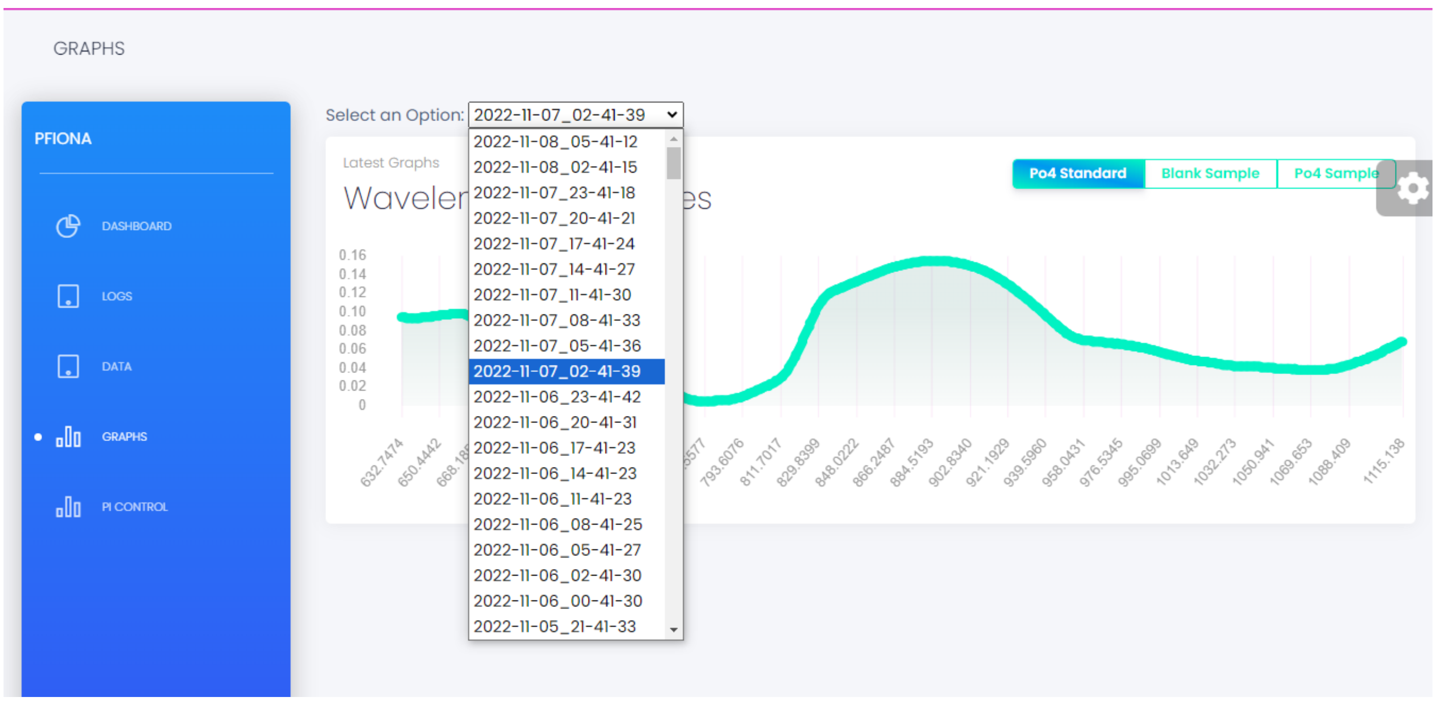

Fig. 8. User Interface: Logs.

particularly crucial in real-time data monitoring and control applications, where timely responses are essential. Additionally, Django's extensive library and support for RESTful API integration streamline the development process, allowing for more rapid and efficient development cycles compared to tkinter. This aspect is particularly beneficial in complex systems where ongoing development and incorporation of new features are required.

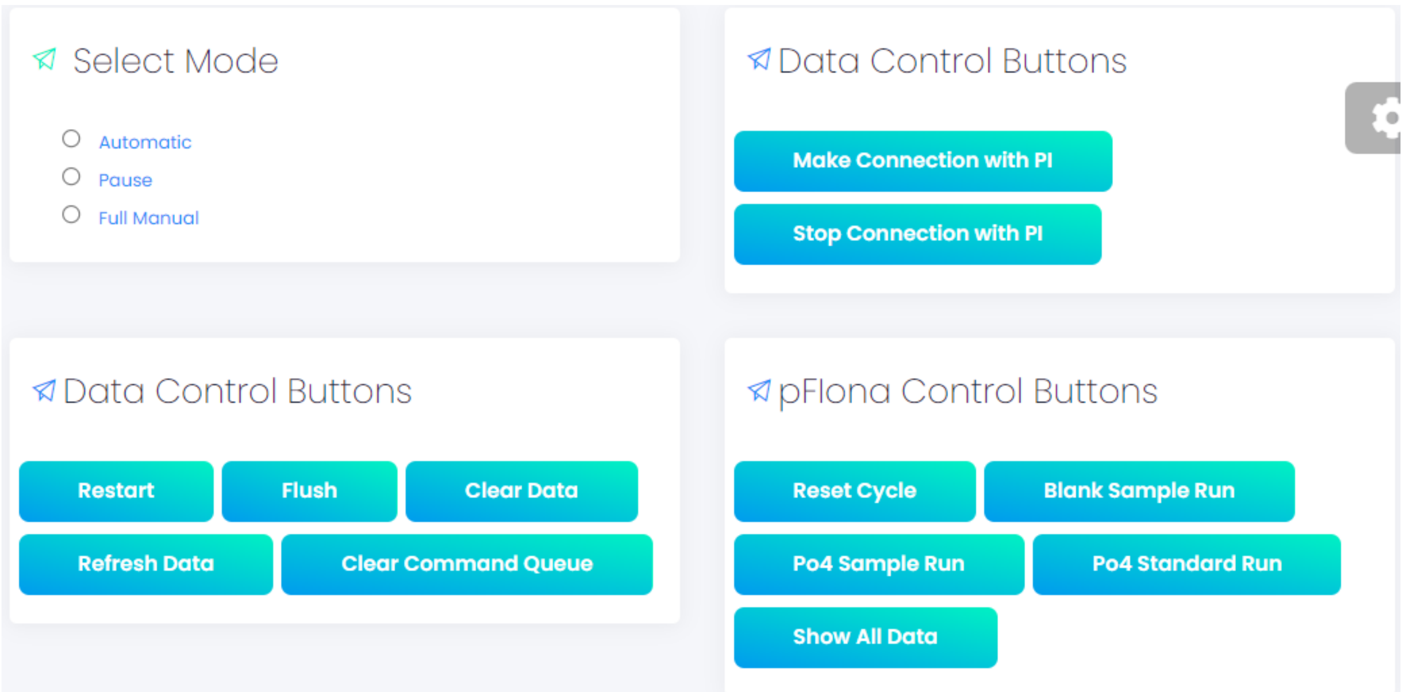

Fig. 9. User Interface: pFiona Controls.

Overall, the user interface stands out as a highly intuitive and comprehensive component of our system. It simplifies the management and monitoring of the system. It enhances the user experience through its well-organized and feature-rich design. This interface is a testament to our commitment to providing a user-centric, efficient, and easy-to-navigate solution.

IV. Evaluation Methodology

A. *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:

- 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.
- 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.
- 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.

B. *Evaluation Strategy*

As we embark on the final stages of our buoy system project, a rigorous and structured evaluation strategy is essential to validate the functionality and reliability of our design. This strategy is methodically divided into several phases, each focusing on different aspects of the system. From unit testing individual components to comprehensive integration testing, and from performance metrics evaluation to submersion testing, our approach is designed to ensure that every element of the system operates optimally and cohesively. The following sections detail each phase of our evaluation strategy, highlighting the methodologies and objectives aimed at affirming the system's readiness for real-world application.

1. Unit Testing

The initial phase of our evaluation strategy encompasses comprehensive unit testing for each component within both the user interface and the power management system.

Power Management System Unit Testing: This involves meticulous testing of each component to validate its functionality. For the solar panels, we assess the output generated under varying levels of light intensity. The charge controller's efficacy is evaluated to ensure compatibility with the battery and panel, alongside adherence to set battery parameters. Battery tests focus on verifying charge and discharge conditions. Voltage converters are examined by applying varying input voltages and observing the consistency of the output. Lastly, the relay switches are tested to confirm their responsiveness to appropriate on and off signals.

User Interface Unit Testing: This testing primarily involves verifying the functionality of individual components, particularly the working of the REST API. Tools such as Postman or similar services are employed to ensure the API's robust

2. Integration Testing

Following unit testing, the next phase is integration testing, which examines the cohesive operation of the system components when connected.

Power Management System Integration Testing: This stage entails verifying the integrated functionality of the power management system once all components are connected and operational.

User Interface Integration Testing: For the user interface, integration testing focuses on manually assessing if the interface can accurately render all elements and maintain operational.

3. Performance Metrics Evaluation

The third phase of testing involves assessing the system against predefined performance metrics under varying environmental conditions. These evaluations particularly focus on different light intensities throughout the day. Additionally, the intermittent operation of the system is manually tested by intentionally interrupting pFiona and then signaling it to resume tasks, thereby verifying its robustness and recovery

4. Submersion Testing and Controller Compatibility

The final testing phase involves submerging the entire system in a controlled aquatic environment. This test is designed to emulate real-world operational conditions and assess the buoy's performance and durability underwater.

In parallel, tests on different combinations of charge controllers, including PWM, MPPT, and a combination of both, are conducted. The goal here is to determine the most compatible and efficient controller setup for the system, optimizing its energy management and overall

In conclusion, our structured evaluation strategy for the buoy system is comprehensive, encompassing unit testing, integration testing, performance metrics evaluation, submersion testing, and controller compatibility assessments. This multi-faceted approach ensures thorough validation of the system's functionality, reliability, and efficiency across various operational scenarios and environmental conditions.

V. Results

The project has reached several important milestones, notably the completion of the buoy design and the implementation of key features such as an integrated power management system, intermittent computing, and Dynamic Voltage and Frequency Scaling (DVFS). However, it's essential to note that the comprehensive evaluation strategy outlined in previous sections is still in the process of being fully implemented.

The verification of the system was further reinforced by completing the unit and integration testing phases as outlined in our methodology. Initial testing phases have been undertaken, focusing on integration verification. These preliminary tests have targeted the validation of the power management system's design, yielding promising results. The tests confirmed the efficacy of the proposed architecture in harmonizing with the load device. Additionally, battery charging procedures were conducted in accordance with manufacturer specifications, successfully affirming the accuracy of the charging curves. This step has laid a foundational assurance of the system's operational reliability.

Despite these encouraging early results, there is a need for more exhaustive testing. Future work will be concentrated on thoroughly evaluating the entire system, particularly focusing on the buoy's performance in its intended operational environment. This phase will encompass extensive testing of all components and subsystems, challenging them under a variety of environmental conditions to test their resilience and adaptability.

The aim of these upcoming evaluations is to corroborate the theoretical design and initial findings and pinpoint potential areas for improvement. This step is vital to ascertain the system's robustness, operational efficiency, and sustainability, which are critical for its successful deployment in marine settings.

VI. Discussion and future works

In this research, we have successfully developed an integrated power management system, incorporating intermittent computing with pFiona and utilizing a Raspberry Pi. Our work included completing a buoy design, implementing a sophisticated battery management system, and integrating intermittent computing with Dynamic Voltage and Frequency Scaling (DVFS).

Looking ahead, the next phase of our project involves the full development and construction of the buoy. This step is critical in realizing the practical application of our theoretical design and research findings. Future work will also focus on conducting extensive validation experiments. These experiments are essential to rigorously test and verify the efficacy of our buoy design and its components in real-world scenarios.

Moreover, a significant aspect of our forthcoming research will be the comprehensive testing of the buoy by deploying the integrated system, including pFiona, in a water-based environment. This testing will provide valuable insights into the system's performance, durability, and reliability when fully submerged in water. It will also allow us to assess the system's operational capabilities in real aquatic conditions, which is crucial for its intended application.

To summarize, the continuation of this research holds the promise of advancing the field of buoy technology, particularly in terms of power management and computational efficiency. The outcomes of the future work are expected to significantly contribute to the practical and effective deployment of such systems in marine environments.

VII. 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.

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APPENDIX 1

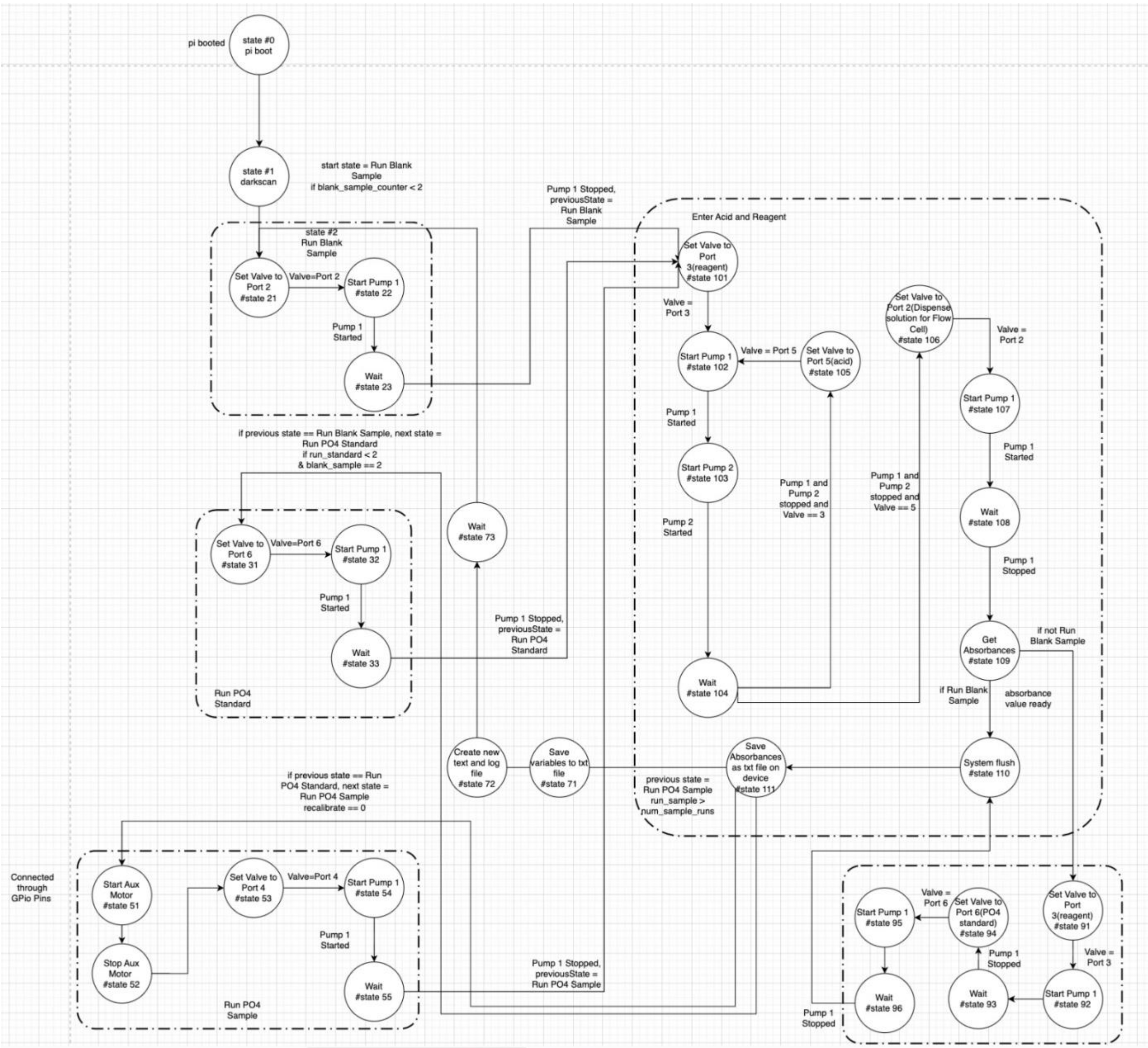

Fig A.1 Decision Tree to determine whether to Run pFIONA

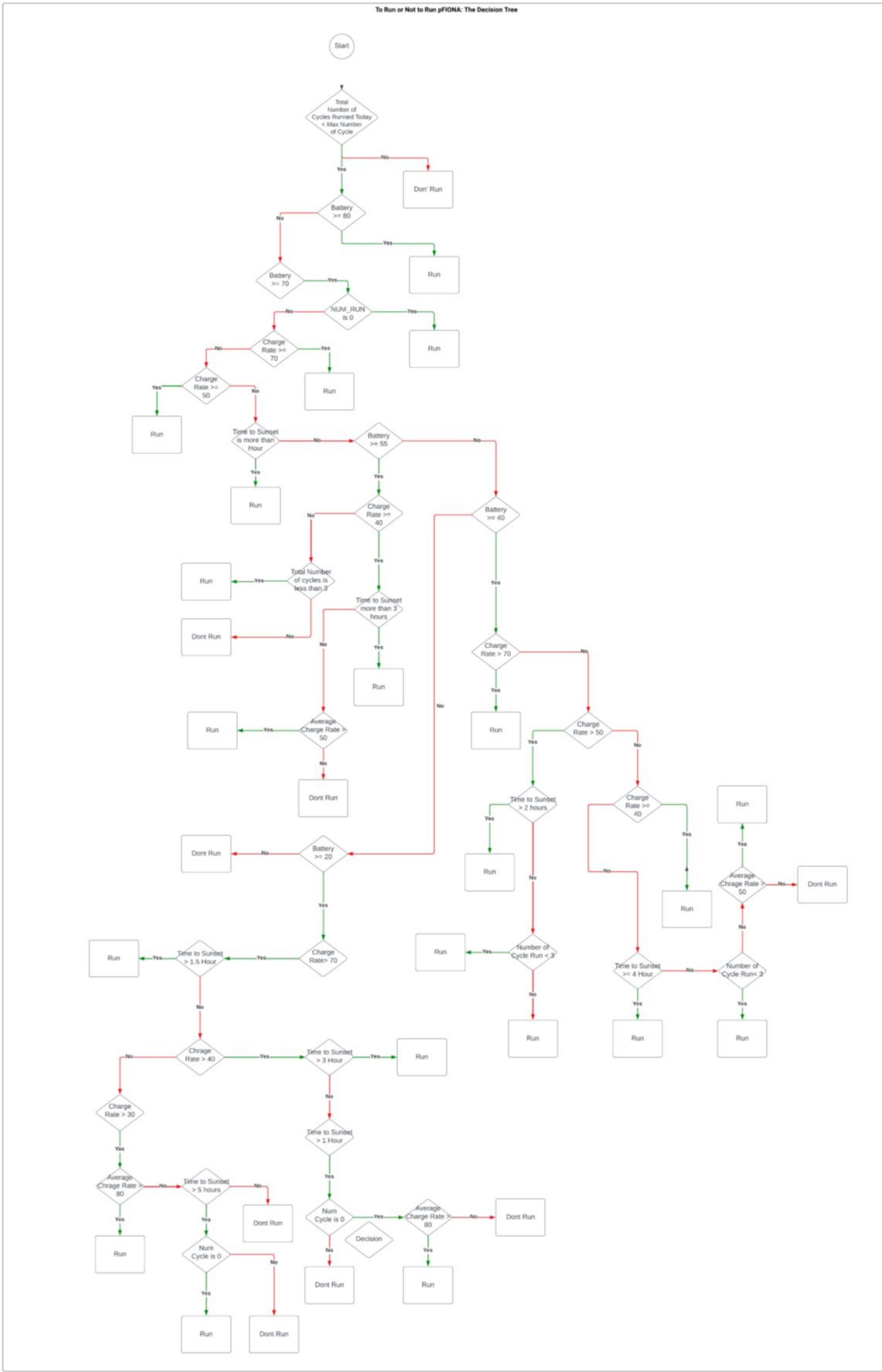

Fig A.2 Decision tree for Nano Board