Implementing an Intermittent Computing System for an Autonomous Ocean Analyzer Prototype

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Master of Science in Computer Engineering
Master of Science in Software Engineering

By

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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.

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Implementing an Intermittent Computing System for an Autonomous Ocean Analyzer Prototype

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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 (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.

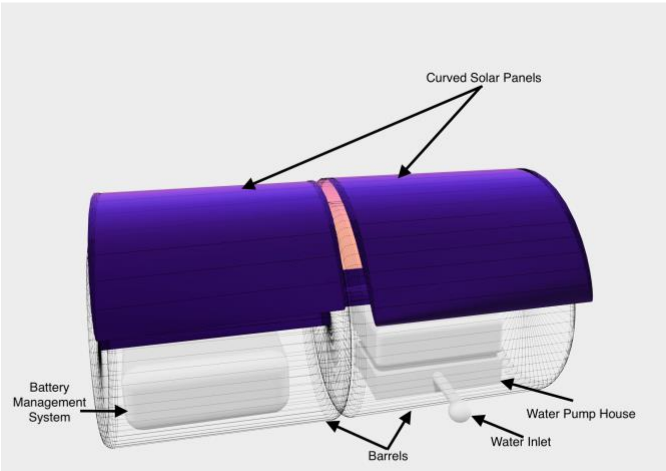

Fig. 1. Conceptual Design of the hull along with the solar panel.

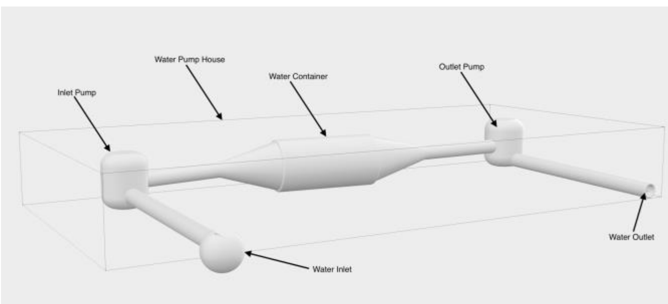

Fig 2. Conceptual design of the water pump

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:

A. 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.
B. 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.
C. 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.

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.

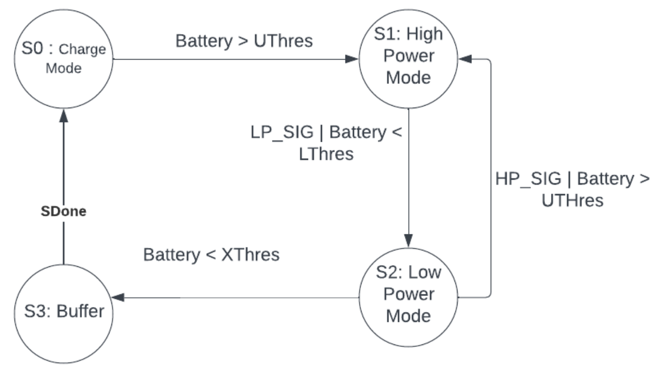

Fig. 3. State Diagram for proposed power system

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.

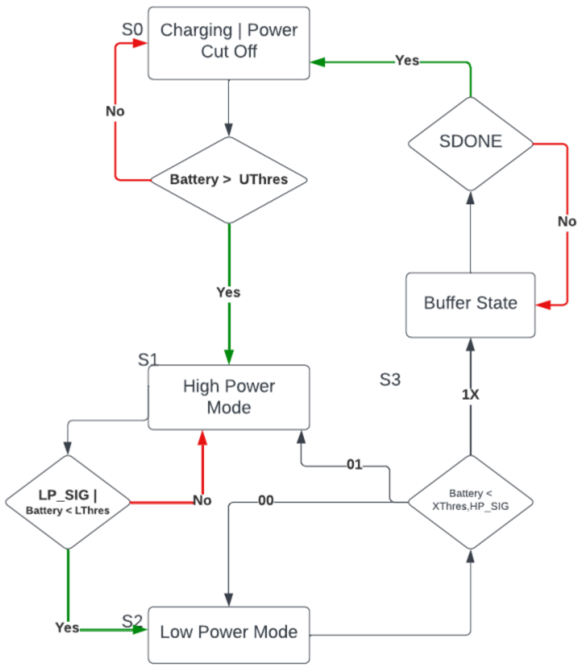

Fig. 4. ASM chart for power system

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 details the comprehensive system design, encompassing four primary components: the power management system, intermittent computing, and Dynamic Voltage and Frequency Scaling (DVFS). The integration and functionality of these components are pivotal for the system's overall efficiency and performance. The last component is the enhanced user interface for pFiona.

A. Power Management System Overview

The power management system constitutes the foundation of the design, featuring several critical elements:

1. Solar panels are the primary source for generating electrical energy and effectively harnessing solar power.
2. Batteries: They play a crucial role in storing the electrical energy produced by the solar panels, ensuring a consistent energy supply.
3. Solar Charge Controller: This component is pivotal in managing battery charging, preventing overcharging and deep discharge. It comes in two variants:
   a) Maximum Power Point Tracking (MPPT): Optimized for larger systems, it regulates voltage by concurrently increasing current and decreasing voltage.
   b) Pulse Width Modulation (PWM): Ideal for smaller setups, this variant moderates surplus voltage while sustaining the current level.
4. Nano Board: Acting as the central control unit, the nano board monitors various environmental parameters and executes decisions based on a pre-programmed decision tree.
5. Light-Dependent Resistor (LDR) Sensor: This sensor measures ambient light intensity, providing essential data to the nano board.
6. Relays and Voltage Converter: These components are integral to maintaining appropriate voltage levels and distributing power effectively.

A. Nano Board's Dual Functions

The nano board is designed with two fundamental responsibilities:

1. Parameter Monitoring: It continuously assesses environmental conditions, including light intensity, battery charge rate, and battery charge level.
2. Decision-Making Process: Utilizing a sophisticated decision tree (illustrated in Appendix Figure 5), the board determines whether to activate 'pFiona', a critical system component. This decision hinges on various factors, including pFiona's usage frequency, battery status, and prevailing weather conditions.

B. Configuration of the System

The system's configuration is meticulously designed for optimal performance:

1. A pair of 12V batteries, connected in series, create a 24V setup.
2. These batteries are linked to the solar charge controller and a voltage stabilizer, ensuring a stable 24V output from fully charged batteries despite the 29v potential production.
3. The solar panels are configured in series to deliver 200W at 24V.
4. Theoretically, each battery's 200W capacity allows a full recharge in approximately four hours.
5. A voltage converter bridges the gap between the batteries and the nano board, adapting the 0-25V range to a more manageable 0-5V range suitable for the nano board.

C. Implementing Intermittent Computing and DVFS

Intermittent computing is principally executed on a Raspberry Pi, incorporating checkpointing states as delineated in Figure 3. These checkpoints are crucial for maintaining data integrity and system continuity. Additionally, DVFS is integrated into the Raspberry Pi, governed by signals from the Battery Management System (BMS) based on the battery's charge level. The operational logic of this process is depicted in Figure 4.

D. Improved User Interface

Our new UI uses the Django REST framework to provide a web-based design. The UI runs on the host (e.g., PC) and communicates through Wifi with the analyzer's controller. It can connect multiple analyzers and switch between them. The UI consists of various tabs and plentiful functionalities within each tab. For example, the dashboard tab shows an overview of pFIONA's status and most commonly used controls; the Log tab shows detailed logs for control and debugging. The data tab shows the history of data collected from the analyzer. Graphs tabs (Appendix Figure 4) provide various visualizations of the collected data. The control tab contains a set of buttons and input boxes to provide detailed control of the analyzer's status and adjust its working parameters.

E. Operational Dynamics of pFiona

Upon the initiation of 'pFiona,' the nano board activates a relay switch, which in turn energizes the voltage stabilizer, ultimately supplying power to 'pFiona.' The communication link between 'pFiona' and the nano board is paramount, particularly when the board detects a low battery state. Under such conditions, the nano board orders' pFiona' to cease operations and secure data. This sequence is triggered by a 'power off' signal from the Battery Management System (BMS) to 'pFiona.' Subsequently, after ensuring that all necessary data is saved and operations are safely terminated, 'pFiona' sends an acknowledgment signal back to the nano board, signaling that it is safe to withdraw the power supply. This interplay of signals ensures a coordinated and safe shutdown of 'pFiona,' preserving system integrity and preventing data loss.

F. *Encapsulation by Hull Design*

The system's architecture adopts a modular approach, segregating the power management system and the 'pFiona' unit into distinct barrels. This modularization offers significant flexibility and robustness, catering to diverse operational needs.

1. Integration with the Water Pump House: The barrel containing 'pFiona' is also equipped with a water pump house, illustrated in Figure 2 and Figure 5. This combination consolidates critical components within a single, manageable unit.
2. Physical Security and Stability of the Barrels: To ensure the safety and integrity of the components, each barrel is secured using steel ropes. The interiors of the barrels are filled with polyurethane foam, providing cushioning and additional protection for the enclosed elements. This arrangement safeguards the systems from physical shocks and vibrations.
3. Innovative Design Inspired by Roly-Poly Toys: The design of the barrels draws inspiration from the principles of roly-poly toys. The barrels maintain their upright position by positioning the center of gravity at the bottom, ensuring stability. This feature is particularly beneficial in aquatic environments where the barrels may experience tilting or flipping. Regardless of movement or orientation, the barrels are designed to revert automatically to their original position, ensuring continuous and uninterrupted operation.
4. Storage of Necessary Reagents: Each barrel designated for 'pFiona' includes compartments for storing reagents necessary for its operation. This design ensures that all required materials are readily available, facilitating efficient and timely processing.

This design highlights the importance of efficiency in energy usage and the adaptability of the system to diverse environmental conditions.

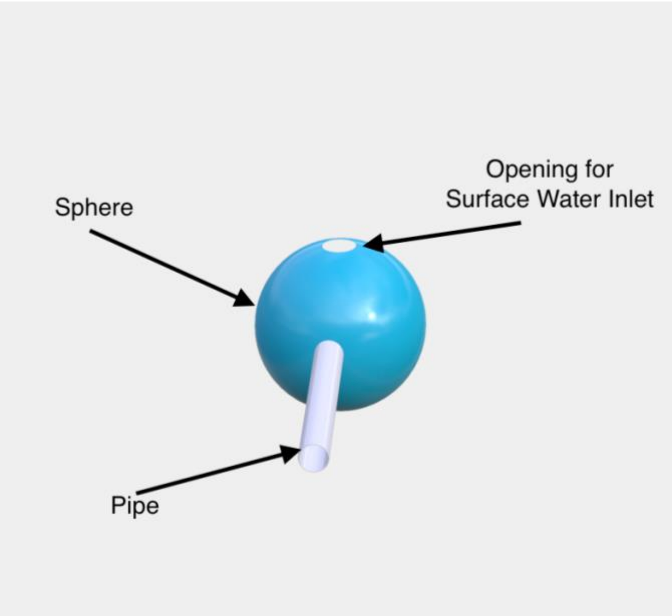

Fig 5. The design is for keeping the Inlet pipe on the surface.

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:

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.

V. 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.

VI. Acknowledgment

We would like to express our gratitude to all those whom this work has made possible. Firstly, we would like to thank our mentor, Dr. Haonan Wang, whose unwavering support and immense knowledge in the field the work was made possible. Furthermore, we would also like to extend our gratitude to Maxime and Moss Laboratory for supporting our work. Lastly, we are grateful to all authors and researchers in the field because of whose contribution we can move forward with the work.

VII. References

[1]. Lotze, Heike K. "Marine biodiversity conservation." *Current Biology 31*, no. 19 (2021): R1190-R1195. Accessed May 28, 2023. https://doi.org/10.1016/j.cub.2021.06.084.

[2] R. T. Masserini, K. A. Fanning, S. A. Hendrix, and B. M. Kleiman, "A coastal surface seawater analyzer for nitrogenous nutrient mapping," Continental Shelf Research, vol. 150, pp. 48–56, 2017. [Online]. Available: https://doi.org/10.1016/j.csr.2017.09.010

[3] F. Azzaro and M. Galletta, "Automatic colorimetric analyzer prototype for high-frequency measurement of nutrients in seawater," Marine Chemistry, vol. 99, no. 1, pp. 191–198, 2006. [Online]. Available: https://doi.org/10.1016/j.marchem.2005.07.006

[4]. M. Lebrec et al., "Developing Autonomous, Open-Source Macronutrient Monitoring Instrumentation: The Programmable Flow Injection Ocean Nutrient Analyzer (pFIONA)," in AGU Fall Meeting Abstracts, vol. 2022, 2022.

[5]. M. Hatta, et al., "An advanced method for the determination of iron (III) and iron (II) in seawater by catalytic spectrophotometric flow injection analysis," Limnol. Oceanogr.: Methods, vol. 19, no. 2, pp. 74-88, 2021.

[6] J. Ruzicka, et al., "Flow injection techniques for the in situation monitoring of marine processes," J. Flow Inject. Anal., vol. 36, no. 2, pp. 123-145, 2019.

[7] J. Kwak, et al., "ICEr: An Intermittent Computing Environment Based on a Runtime Module for Energy-Harvesting IoT Devices with NVRAM," Electronics, vol. 10, no. 8, p. 879, 2021.

[8] S. Ahmed, et al., "Efficient intermittent computing with differential checkpointing," in Proc. 20th ACM SIGPLAN/SIGBED Int. Conf. on Languages, Compilers, and Tools for Embedded Systems (LCTES 2019), New York, NY, USA, 2019, pp. 70-81.

[9] J. Henkel, "A low power hardware/software partitioning approach for core-based embedded systems," in Proc. 1999 Design Automation Conf., New Orleans, LA, USA, 1999, pp. 122-127.

[10] R.A. Kjellby et al., "Self-powered IOT device based on energy harvesting for remote applications," in Proc. 2018 IEEE International Conference on Advanced Networks and Telecommunications Systems (ANTS), 2018.

[11] S. Ahmed, et al., "Poster Abstract: Towards Smaller Checkpoints for Better Intermittent Computing," in Proc. 2018 17th ACM/IEEE International Conference on Information Processing in Sensor Networks (IPSN), Porto, Portugal, 2018, pp. 132-133.

[12] E. Aras, et al., "A Low-Power Hardware Platform for Smart Environment as a Call for More Flexibility and Re-Usability." in Proc. 2019 International Conference on Embedded Wireless Systems and Networks, EWSN 2019, Beijing, China, February 25-27, 2019.

[13] H. Wu, C. Chen, and K. Weng, "An Energy-Efficient Strategy for Microcontrollers," Applied Sciences, vol. 11, no. 6, p. 2581, Mar. 2021, doi 10.3390/app11062581.

[14] A. Bhattacharyya, A. Somashekhar, and J.S. Miguel, "NVMR," Proceedings of the 49th Annual International Symposium on Computer Architecture, 2022. [Online]. Available: https://doi.org/10.1145/3470496.3527413.

[15]. G. Dhiman, R. Marchetti, T. Rosing and V. Le, "vGreen: a system for energy-efficient computing in virtualized environments," in ACM Transactions on Architecture and Code Optimization (TACO), vol. 7, no. 3, pp. 1-23, 2010.

[16] V. Hanumaiah and S. Vrudhula, "Energy-efficient operation of multicore processors by DVFS, task migration, and active cooling," in IEEE Transactions on Computers, vol. 63, no. 3, pp. 349-360, March 2014.

[17] W. Kim, M. Gupta, G. Wei and D. Brooks, "System level analysis of fast, per-core DVFS using on-chip switching regulators," in IEEE International Symposium on High Performance Computer Architecture, Salt Lake City, UT, USA, pp. 123-134, 2008.

[18] A. Bartolini, L. Benini, A. Tilli and F. Menichelli, "Prediction Models for Dynamic Voltage and Frequency Scaling in Multicore Processors: A Design Space Exploration," in IEEE International Symposium on Modeling, Analysis and Simulation of Computer and Telecommunication Systems, London, United Kingdom, pp. 350-359, 2016.

APPENDIX 1

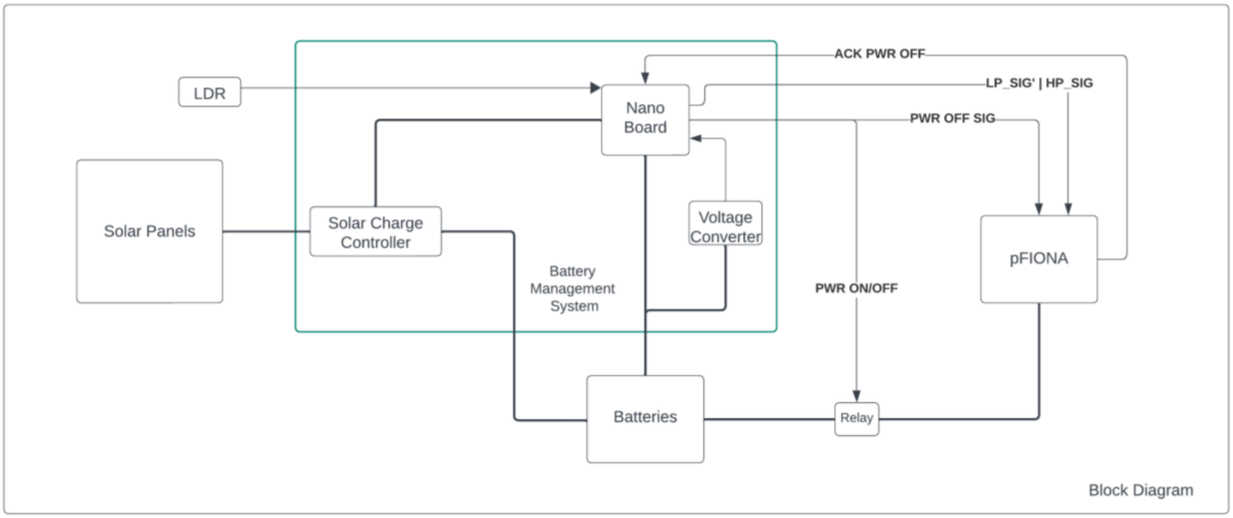

Fig A.1 Block Diagram of the proposed system.

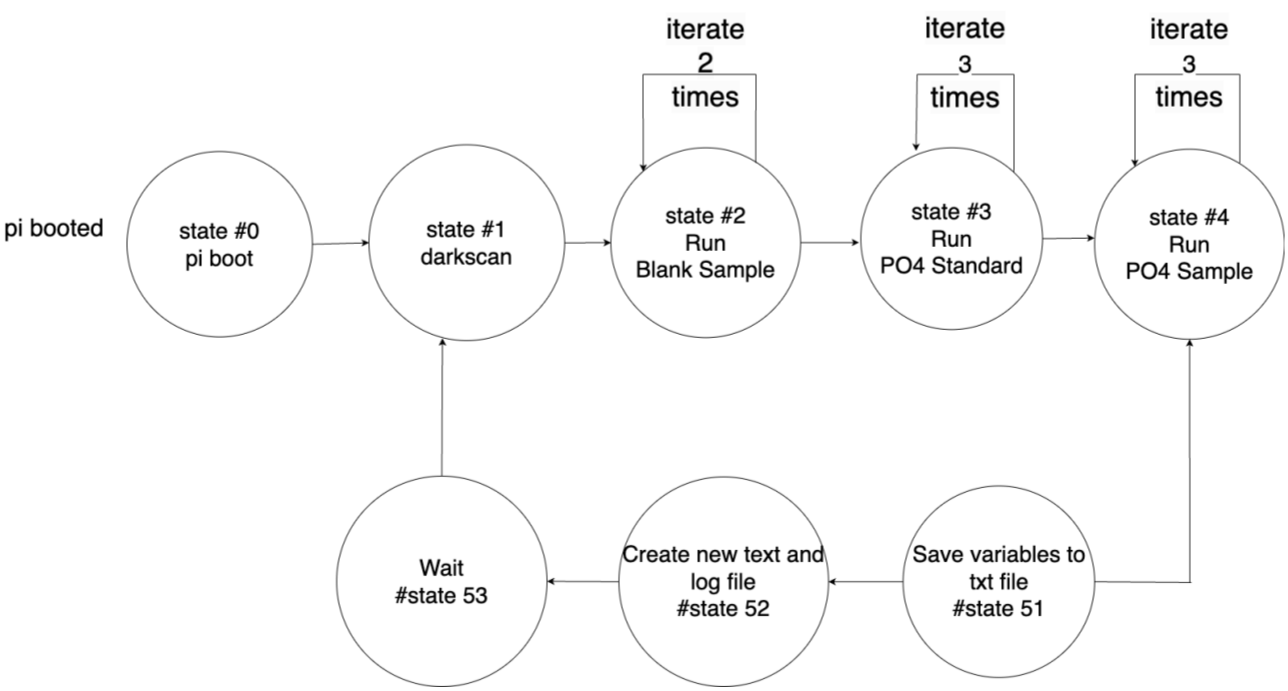

Fig A.2 State diagram for pFiona

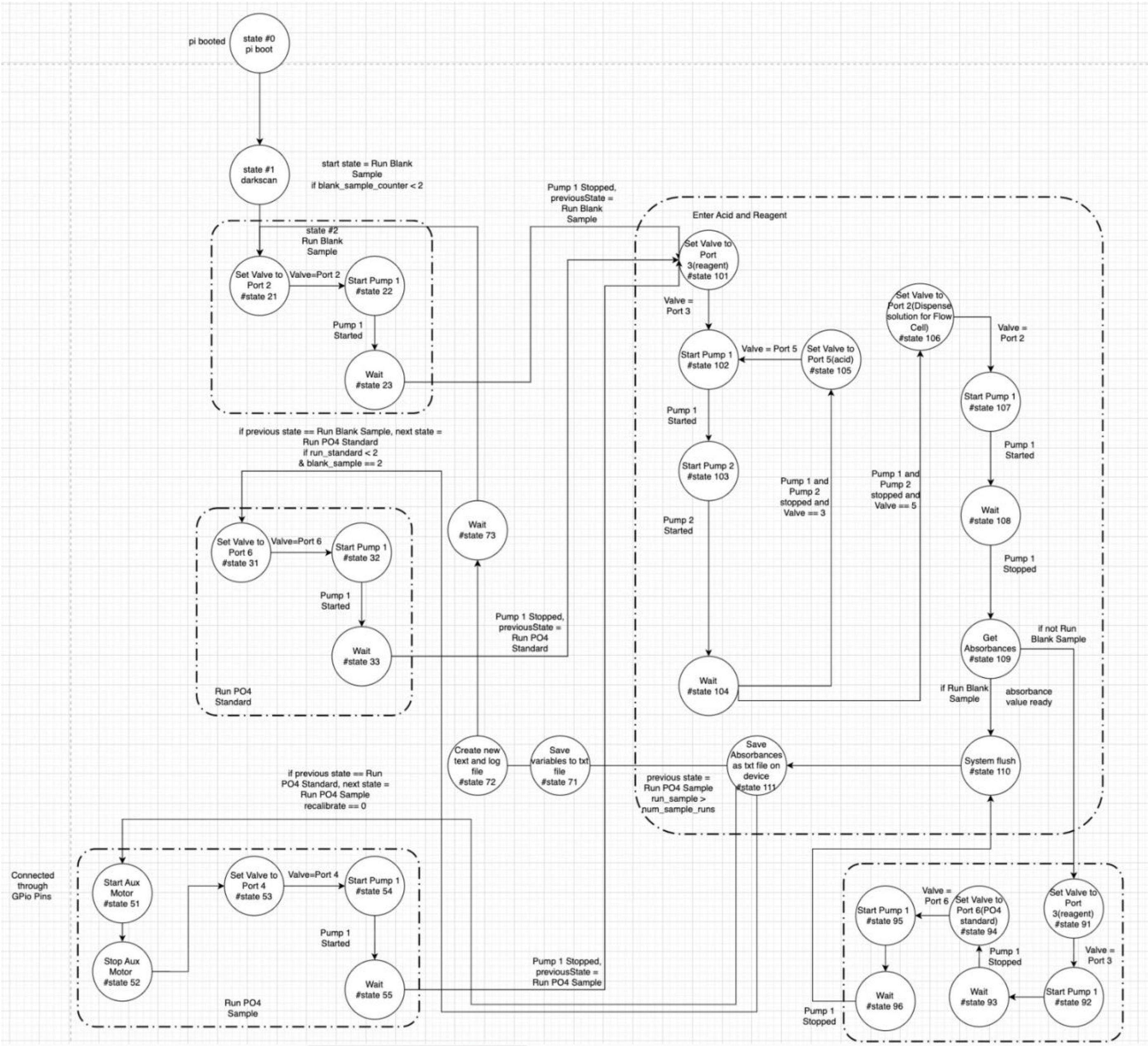

Fig A.3 Decision Tree to determine whether to Run pFIONA

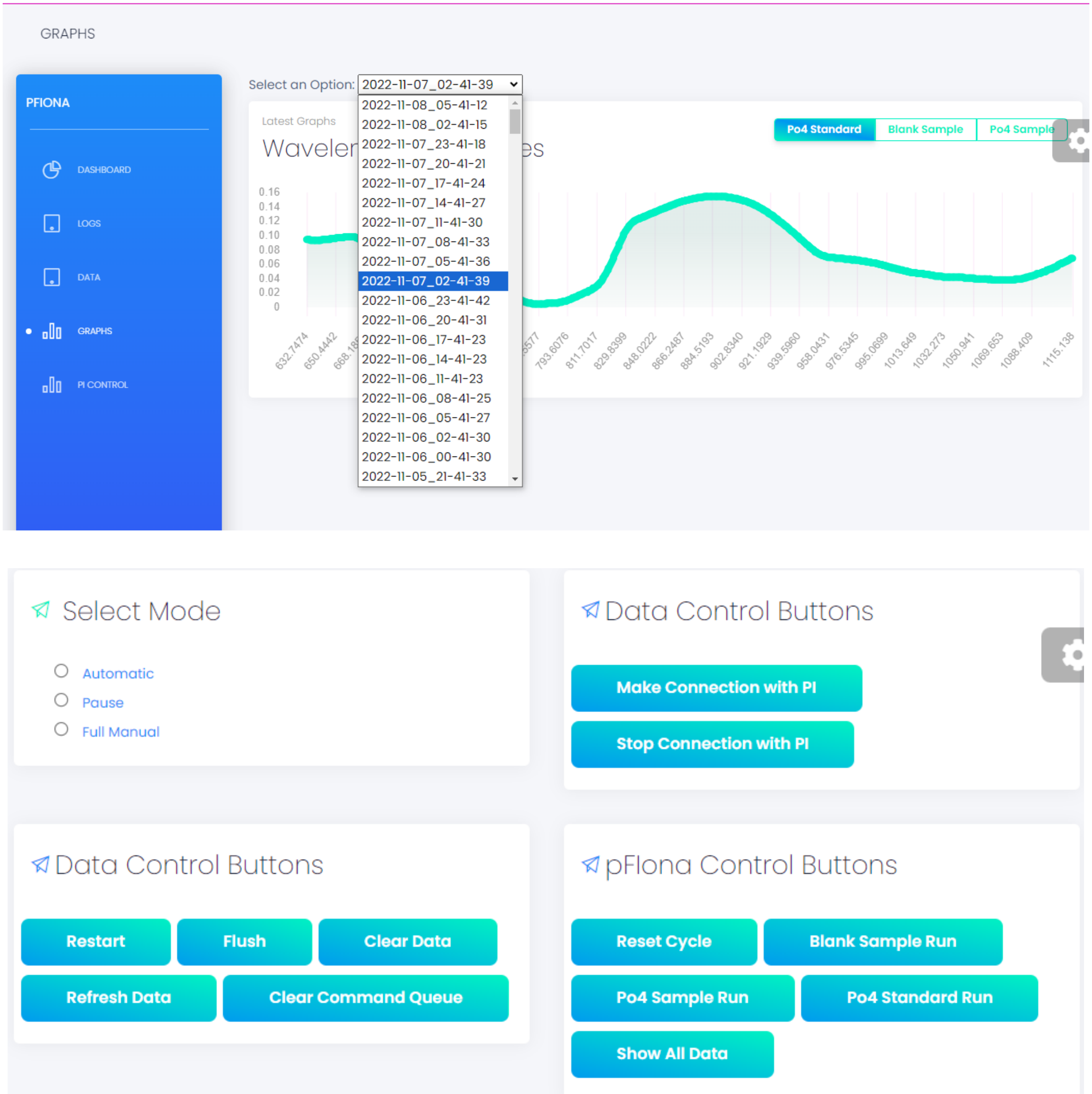

Fig A.4 Snapshots of User Interface.

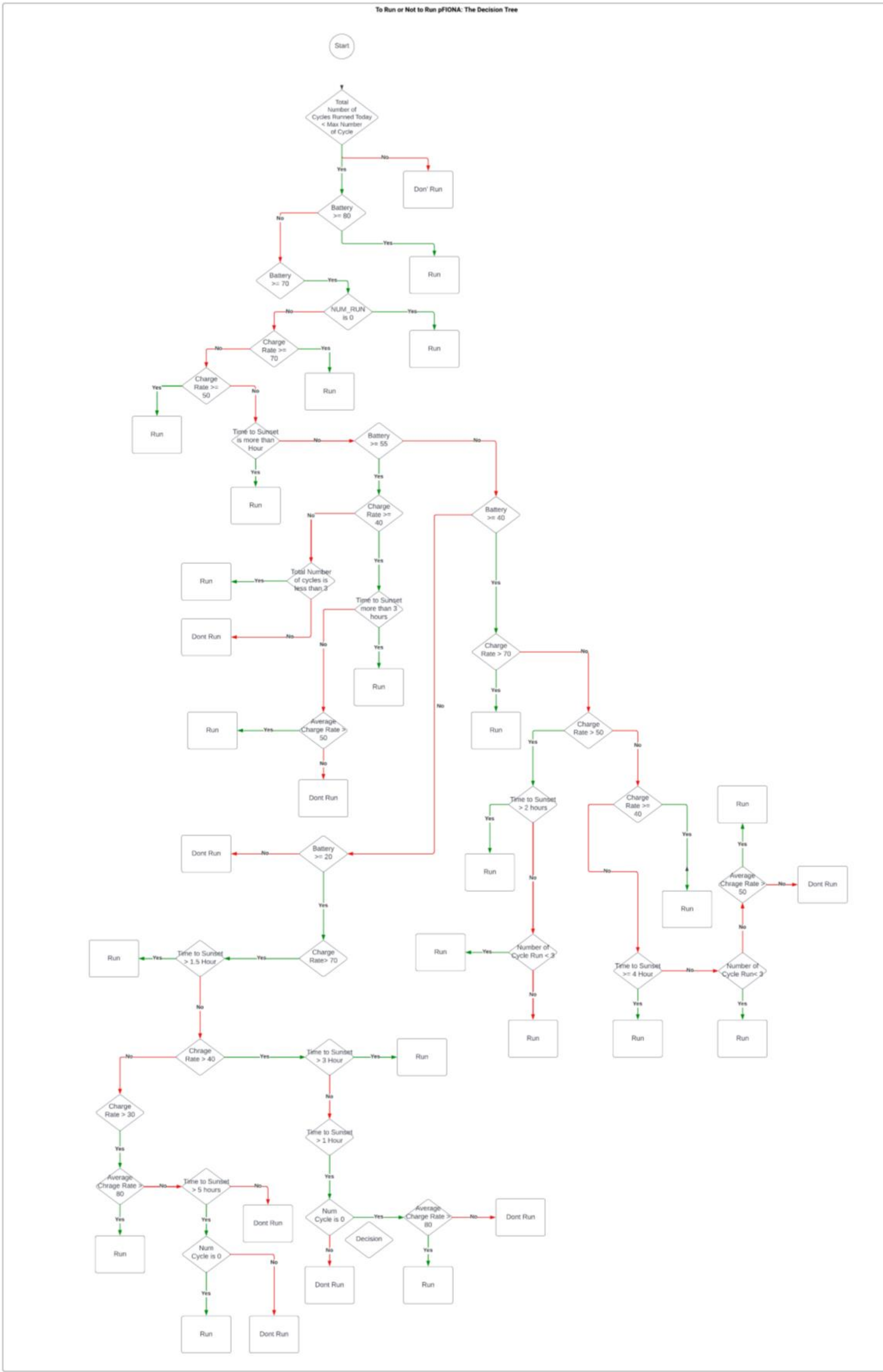

Fig A.5 Decision tree for Nano Board