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Intelligent Hybrid Power Plant for Marine Hydrogen Fuel Cell Integration

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Abstract

This paper presents a senior undergraduate capstone project from a multidisciplinary team of mechanical and electrical engineering students at the U.S. Coast Guard Academy. The project focuses on developing a hybrid power plant system that combines hydrogen fuel cells, photovoltaic solar panels, and lithium-ion batteries specifically designed for maritime applications. Hydrogen is increasingly recognized as a critical alternative fuel for the future of maritime operations, presenting both opportunities and challenges with its implementation. Hydrogen fuel cells offer a promising zero-emission solution for vessel propulsion. However, their effective integration with existing maritime power systems requires consideration for practicality, safety, and regulatory compliance.

At the core of this project is a control algorithm designed to intelligently manage power distribution among the three power sources, ensuring that the hybrid system can meet the real-time load demands of a one-watt electric propulsion system on a small-scale displacement vessel. The control system, consisting of an Arduino Mega, utilizes a dynamic balancing strategy that adjusts the input from a Hydrostik Pro fuel cell, multiple small-scale solar panels, and a 6Ah Li-Po battery based on the vessel's operational profile and energy requirements. Key performance metrics, including response time and system stability, were rigorously evaluated through simulations and practical testing. The results indicate significant improvements in power source integration and compliance with the demands of the maritime industry, affirming the practicality of this integrated approach. The successful implementation of the hybrid power system on a small, remote-operated vessel propelled by two 6V DC motors is a tangible proof of concept, illustrating its applicability within current regulatory frameworks governing hydrogen fuel cell safety and maritime emissions.

The project has successfully constructed a basic control system that can bring together solar power, Lithium-Ion batteries, and hydrogen fuel cells to drive the intended load of this proof-of-concept vessel. The basic controller also includes a MATLAB Graphical User Interface, which visualizes data in real-time and sheds light on the patterns and behavior of these sources. Finally, research continues to be carried out to set the path for the autonomous implementation of the control system in upcoming phases. This paper highlights intelligent hybrid control systems' growing importance and advancement in modern power production.

Introduction

As the maritime industry increasingly explores hydrogen-powered vessels, the insights derived from this study will play a critical role in shaping the Coast Guard's perspective on adopting and regulating hydrogen technologies to enhance maritime safety and environmental stewardship. Ultimately, this project advances the technical understanding of hybrid hydrogen systems while highlighting the educational significance of interdisciplinary collaboration in addressing the complexities of sustainable marine energy solutions.

With the rise of hydrogen power technology in the maritime domain, the US Coast Guard must work to understand this energy source that is entering its regulatory jurisdiction. One perennial problem affecting hydrogen power systems is how to optimally control fuel cells to be safe and efficient. This project seeks to improve the Coast Guard's experience with the control systems put in place to integrate hydrogen power with other sources of energy, as well as a desired load. Setting the goal of fabricating a remote-operated vessel that uses an autonomous power system, this project embarks on the path to bring a more 'intelligent' design into power management for hybrid maritime vessels.

When hydrogen power is mentioned in today's world, the first thing that comes to mind is the tragedy of the Hindenburg, a blimp filled with hydrogen gas that exploded and cost dozens of lives [1]. However, as the world turns to alternative energy sources, the stigma toward hydrogen is beginning to change.

In July 2024, the world's first hybrid hydrogen-powered ferry vessel, Sea Change, was launched in San Francisco [2]. With hydrogen fuel cells entering the maritime domain, the US Coast Guard is left with the challenge of regulating the novel technology, navigating a public perception wary of such energy sources, and ensuring that innovation can still be fostered even under the umbrella of strict safety standards. the US Coast Guard invests resources, personnel, and time into understanding the integration of hydrogen power and its implications. The question remains as to how such a feat can be accomplished.

The key development that has made hydrogen power viable again is a novel way of cultivating its chemical energy. In the past, the only way to cultivate hydrogen power has been through combustion, an inherently dangerous process. However, recent developments have led to the creation of fuel cells to produce energy from hydrogen.

Fuel cells operate in ways similar to a battery. Hydrogen is introduced at the cell's anode and oxygen at the cathode. From there, the protons of hydrogen are exchanged with oxygen through a Proton Exchange Membrane (PEM) [3]. To even out the difference in charge, the electrons in hydrogen then become attracted to the oxygen side. Electrons flow from the anode to the cathode through the intermediary membrane, allowing electricity to be extracted to power an external circuit. Fuel cells differ from batteries as more fuel can be added as the circuit runs, allowing for continuous electrical energy generation. Such a mechanism offers a way of providing electrical energy without the risk of combusting hydrogen, all while producing only clean water and oxygen as its exhaust.

While hydrogen fuel cells offer many advantages, they are by no means the perfect energy source. First, the logistics of hydrogen become problematic. Hydrogen is difficult to produce and transport on a large scale, introducing high costs that pose barriers to its regular use. Secondly, while hydrogen for fuel cell applications no longer purposefully combusts, it still must be stored in a safe way to prevent accidental explosions. Such a dilemma means that the safety systems behind fuel cells and their supply reservoirs require significant planning and resources. Finally, the performance of hydrogen has its limitations. As hydrogen power is a chemical process, it takes time to generate power. Thus, while hydrogen might be optimal for steady-state loads, its response time could be lacking for loads that require quick changes or impulses [3].

Such limitations have led to a growing realization that in a world requiring alternative fuel sources, a multi-pronged approach is needed. Integrating multiple systems together can alleviate the individual disadvantages of alternative energy sources by relying on their complementary strengths [4]. For instance, solar power can store energy in a battery that will help provide quick responses to load demands that hydrogen cannot. Furthermore, hydrogen could provide reliable power at night when solar panels would no longer produce energy.

As the integration of multiple alternative energy sources becomes a focal point for future energy grids, a question then arises of how to best manage these increasingly complex systems. With advances in computing, more tools are available to tackle this challenge. No longer are systems limited to simple Proportional-Integral-Derivative (PID) controllers that are manually designed [5]. Rather, more intelligent control systems for these power sources can be produced using machine learning and artificial intelligence [6].

Intelligence in terms of a control system is defined as a controller that autonomously manages the power system for a desired load given a set of internal and external data points [7]. Its decisions should allow for the hybrid system to appear as a seamless unit for the operator of the load. Thus, with intelligent control, hybrid alternative energy systems can be further optimized and better serve as a substitute for traditional fuel sources. Shifting from a traditional system to more intelligent control allows for the disadvantages and advantages of each source to be leveraged appropriately to power the desired load. As hydrogen and hybrid power become more prominent, the use of intelligent systems continues to transition from an experimental novelty to a necessity.

Sea Change: A Real-World Case Study

The world's first all-electric hybrid hydrogen fuel cell commercial passenger vessel, Sea Change, in Figure 1, offers a demonstration of how many of these aforementioned concepts have already been implemented, as well as the obstacles that have yet to be overcome. The Sea Change is successful in the sense that it has been able to serve as the ferry vessel for a major transit route of the San Francisco Bay. It has done this while being powered completely by Hydrogen and Lithium-Ion batteries. Furthermore, its novel safety protocols and operations have been crafted and approved by the United States Coast Guard. All of these accomplishments highlight the potential of hydrogen and hybrid systems to provide power for real-world applications.

Fig. 1: Passenger Vessel Sea Change [2]

However, more still must be done before the technology of Sea Change becomes the norm for the maritime industry. The autonomous control system of Sea Change is still not deemed "intelligent." Due to its lack of ability to take in external and internal data points, the operator must manually sense when the power system cannot hold its own as load requirements shift. Thus, the operators of Sea Change are often forced to shift to manual control and manage the hybrid system themselves, switching between hydrogen and battery power. The result of this is that Sea Change does not work at its optimal level. This is highlighted by the fact that it has a cruising speed of about half that of other ferries in San Francisco, relies on manual control without mechanisms to use hydrogen as efficiently as possible, and has suffered situations where it has had to ration power during transit due to system failure.

While hydrogen and hybrid systems have entered the maritime domain, an intelligent control system is crucial to optimization and making them mainstream. Implementation of these new technologies is complex and multivariable, indicating the need for a system that can handle such a multifaceted challenge.

Thus far, the US Coast Guard has been involved in making the Sea Change a safe vessel and enacting new policies focused on the safe operation of hydrogen on the water. The safety systems on board lay a foundation for control systems to operate based on numerous internal data points and sensors. However, these measures that are put in place have only pertained to the mechanisms of safety for Sea Change. They are not utilized to aid in the efficiency or optimization of the ship's power system. Furthermore, Sea Change lacks external data points such as tidal currents and weather to anticipate load requirements and manage the power systems accordingly.

While the USCG has helped erase the stigma of hydrogen as a dangerous alternative fuel source, more work must be done to help integrate hydrogen with other systems and provide the 'intelligence' to make such technology viable.

Intelligent Hybrid Power Plant Milestones

Considering the above challenges, this project aims to develop a cohesive, intelligent hybrid power plant that integrates hydrogen fuel cells with other energy sources to produce consistent, reliable energy. Such a project would further develop the field of merging different alternative fuel sources together. Furthermore, incorporating an intelligent control system for this hybrid power plant would allow a greater understanding of how modern computing techniques can be utilized in this burgeoning field. With the objective set, the next goal of this project is to identify the benchmarks that would label the created system a success. Overarchingly, an intelligent hybrid power plant's control system could be labeled a success if it manages to switch between power sources for the load without the operator being aware of such changes. To achieve this, specific system requirements are outlined:

- Purely autonomous switching between sources.
- Adequate power generated for 99% of an operational time interval.
- The power controller response time is within one second of fluctuating load demands.
- Capable of operating in a variety of weather conditions.
- Utilizes internal performance measures gathered through sensors to make decisions.

- External sensors are employed to take in environmental factors to make decisions.
- Power reserves store enough energy for 1 minute of operation without power generation.
- Power sources supply 5% surplus energy to the system.

These criteria are set to narrow down the definition of an ‘intelligent hybrid power controller’ from a subjective seamless feeling of the operator to an objective measure of data points. The system’s requirements dictate the level of adaptability and functionality that the power grid will have, making contingencies for events such as complete power loss or offline energy sources. These factors all influence the overall behavior of the control system to lend credit to the feeling of ‘seamless’ vessel operation.

With the goal for ‘intelligence’ now set, the focus is on which exact energy sources would be used for a hybrid power plant. The choice behind the other two sources that would accompany hydrogen is based on their advantages and disadvantages relative to hydrogen fuel cells. Moreover, higher weights were given to the factors of these sources that could complement hydrogen to achieve the outlined system requirements jointly. Taken into consideration are the following capabilities and limitations of hydrogen fuel cells:

- Slow response time
- High energy yield
- Energy supply is not influenced by environmental factors

A Talentcell 6Ah Li-Po battery bank is the first source to accompany hydrogen in this project. Such a battery would respond faster to increased load demands than hydrogen [8]. While unable to generate their own energy, batteries can be recharged by other sources, such as hydrogen fuel cells or solar panels, making them resilient to environmental factors.

Multiple small-scale solar panels are selected as the second source to generate their own electricity and to provide redundancy should the hydrogen fuel cell fail. Furthermore, to properly test the system requirement, the second source should be variable based on the system uncertainty. Solar panels have a much shorter response time than hydrogen and can also generate their own electricity [9]. However, with that comes a power-generating ability that is subject to the natural fluctuations of the sun and the weather from above.

The load was selected to be dynamic and relatively indeterministic to meet the system requirements. Additionally, some operators could be used to test the seamless power system operation. Finally, since the foundations for this project are rooted in advances in technology within the maritime domain, a load with maritime-related applications would be preferable. Thus, the load is selected to be a remote-controlled small-scale boat. The nature of a vessel traveling on water controlled by a human would create the desired relatively indeterministic and dynamic load. The remote-control aspect would achieve the operator's requirement. Finally, creating a boat would enable the objective to directly relate to the maritime domain, serving as a case study for what other vessels, such as Sea Change, could one day implement. A small-scale, desktop-sized boat was decided upon for the load due to resource constraints and the fact that the load is serving a project whose purpose is research and prototyping. Therefore, a larger-scale, passenger-sized boat is not feasible nor in line with the spirit of this project.

The objective set and defined is implied above; the next step is to create a timeline of events for this project throughout two sixteen-week periods, i.e., two semesters. To do so, four phases were mapped out:

Phase I	Power system understanding
Phase II	Intelligent control design
Phase III	Real-world implementation
Phase IV	System optimization

Phase I starts with the foundations of the end-goal deliverable. This phase has the aim of gathering important data on the different energy sources used for this project. Such an endeavor sought to be able to fully understand and explain the behavior of all three sources. The final deliverable for this phase would be a basic controller that could manually toggle between three sources, collecting data through the entirety of its operations. Due to the large body of knowledge needed to undertake this project, this phase was allocated the most time. Completion for this phase was aimed for the first semester.

Phase II consists of building onto the basic controller from Phase I. Essentially, the goal of this segment of the project is to begin the creation of an autonomous system. Furthermore, this phase aims to increase familiarity with and employ modern computing techniques such as machine learning to create a highly efficient controller that would not only employ internal data such as current and voltage, but also external data points such as weather. The deliverable for this phase would be a completely autonomous system that begins to meet the criteria for success outlined previously. The target date for completion of this phase is the middle of the second semester.

Phase III consists of merging the controller with the real-world hardware of the remote-controlled boat. This phase seeks to apply the concepts and prototype of the autonomous system to the dynamic maritime environment. The deliverable for this phase is a remote-operated vessel that achieves all the criteria for success outlined previously. The target date for completion is the beginning of the last quarter of the second semester.

Phase IV consists of continuing to optimize the now real-world control system. By placing the controller in a dynamic environment, data will be captured relating to the power system and the state of the vessel itself. Applying this data and the foundations for 'intelligent' control designed in Phase II, this phase aims to further optimize the power control system. The deliverable for this project is an analysis of the system's performance as well as the next steps that will be taken in future research to continue to improve the efficiency of this power system. The target date for completion is the end of the second semester.

The overall target of this project will be achieved through these four phases. Additionally, the system requirements outlined will ensure that the benchmarks for these phases have tangible metrics. With these structures provided for the project, the next steps are to detail the outlined goals.

Product Conceptual Design

To begin the design process, the first step taken is to lay out the foundations of what the final remote-operated vessel would look like. To meet its required goals, it would have to consist of a sea-worthy small craft that could maneuver in the water, a control system that could interact with a remote user, a series of power sources (specifically hydrogen fuel cells, a battery bank, and solar panels) to provide hybrid energy, and an intelligent control system to supervise the power system itself. Thus, the final design would need to consist of four main components:

i. Seaworthy structure and propulsion system
ii. Maneuvering control system with remote capabilities
iii. Hybrid energy power sources
iv. Intelligent power control system

Figure 2 shows the system diagram demonstrating the interactions between these four components and the ancillary components required for their interconnection.

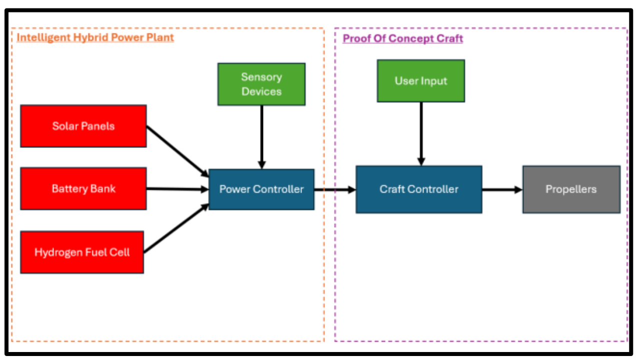

Fig. 2: System Diagram

This conceptual layout for the end-goal product aims to provide a clear vision to direct progressive system design measures throughout the entirety of this project. Furthermore, by breaking the final envisioned product into components, a modular approach can be implemented for this project's design phase, albeit with the overarching objective of creating an intelligent hybrid power system. With this framework, modules such as the boat's propulsion systems and structure could be seen as constraints and loads on the power system rather than taking focus away from the power system research itself.

Design Specifications

The first part of the design was the load that the power system would be attached to. For this, parallel motors would be used instead of implementing a rudder for steering control to simplify the design, as shown in Figure 3. By having two motors, the boat would be able to 'twist' into a desired direction through controlled uneven power distribution to each motor. This decision allowed the propulsion system to consist entirely of one type of electrical component whose properties and behavior, such as power usage, RPMs, and torque, could be measured and provide viable data to the intelligent control system.

Fig. 3: DC Motor Configuration

Table 1: DC Motor Specifications

Voltage	*6V*
Current	*150 mA*
Speed	*20,000 RPM*

Power Source Procurement

With the given load set, the next design challenge was to find power providers that used the energy sources specified in the objective (hydrogen, solar, and battery). Seeing that the DC motors required 6 V and 150 mA, the following sources in Table 2 were found to be within the desired range for successful load power provisions. Pictures of these sources are shown in the Figures. 4, 5, 6, and 7.

Table 2: Power Source Ratings

Source	Current	Voltage	Power
10W Fuel Cell	*1.67 A*	*6 V*	*10 W*
200W Fuel Cell	*13.3 A*	*15 V*	*200W*
Lithium-Ion Battery	*6000 mAh*	*6.4 V*	*38.4 Wh*
Solar Panel	*0.166 A*	*7 V*	*1 W*

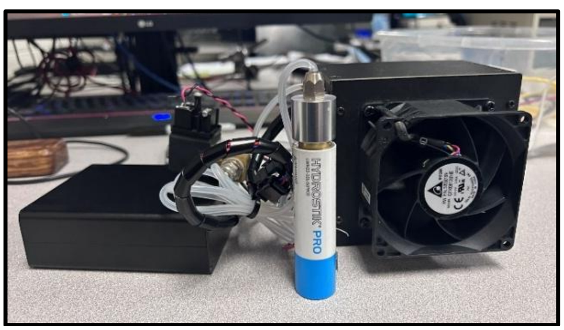

Fig. 4: 200W Hydrogen Fuel Cell and Hydrostik Pro

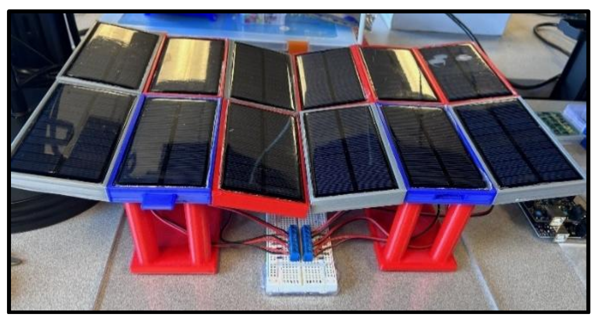

Fig. 5: Solar Panel Configuration

In this project, the hydrogen is stored in metal hydride storage devices, known as Hydrostiks, each with a storage capacity of 10 liters [10]. A 10W and a 200W fuel cell were initially tested with these Hydrostiks.

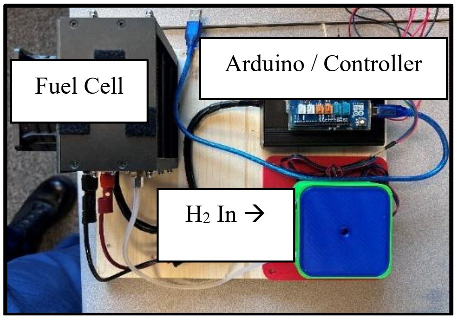

Fig. 6: 200W Fuel Cell Configuration

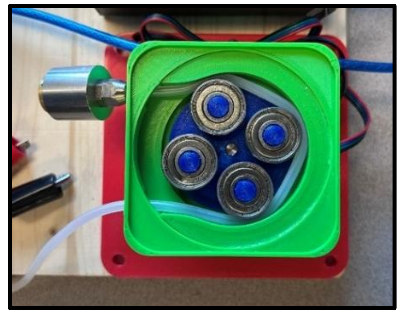
Fig. 7: Peristaltic Pump

In this project, twelve 2x4 inch solar panels were connected in parallel to maximize current output, meeting the load requirements of the system. The parallel configuration ensures that even if one panel experiences a drop in performance due to shading or other environmental factors, the overall system output remains stable, as shown in Figure 5. The technical specifications for these panels are listed in Table 3.

Table 3: Solar Panel Specifications

Surface Area	*66 cm²*
Maximum Power	*1 W*
Operating Current	*0.1666 A*
Working Voltage	*6 V*

Basic Power Control

With both the specific power source and load components set, the next step was to create a connection between the two. Not only would this connection allow for the safe, effective transfer of power between sources and load components, but it would also allow for different power sources to be toggled on and off by some user input. In essence, this phase of system design sought to create a manual power control system through which a more intelligent system could one day operate. The Relay Circuit Schematic is shown in Figure 9.

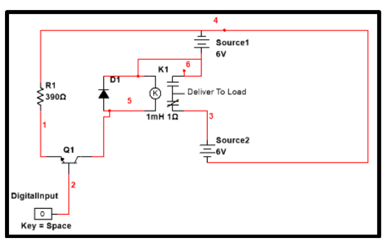

Fig. 9: Relay Circuit Schematic

For the user input and logical side of the power control system, it was decided to use an Arduino Mega. The reason for using this particular device was that it could be utilized for other purposes as well, such as load control and data gathering. Furthermore, Arduinos are user-friendly and easy to attach other components to, a much-needed capability for the modular design of this project.

The load control of the project had one main purpose: to control each motor's speed, direction, and state (i.e. whether or not the motor should be able to move). Due to these constraints, an H-bridge was used for each DC motor. An H-bridge uses a series of transistors to define a DC motor's direction and state [11]. Pulse Width Modulation (PWM) could also be applied to the H-Bridge to control the motor's speed. PWM consists of sending pulses over a certain duty cycle to a motor. This allows a digital signal to act as an analog signal, meaning that the power provided can range from zero to one-hundred percent of a full digital high [12]. Thus, the L298N motor driver was utilized for this design. A picture of the L298N is in Figure 10.

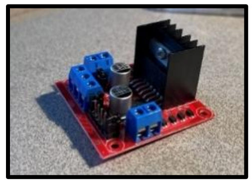

Fig. 10: L298N Motor Driver

The inputs to this H-Bridge would be controlled by the same Arduino Mega set to control the power sources.

The DC0-25V voltage sensor was the first sensory device added to the design to measure the voltage from the motor's upstream node to ground. Additionally, another voltage sensor was added to measure the voltage difference across a motor, which would then be divided by the motor's resistance to yield the current. The reason why this was done instead of using a current sensor was that the design process was simplified by using the same component twice while still yielding the desired results. For this design, a DC0-25V voltage sensor was used and is pictured in Figure. 11.

Fig. 11: DC0-25V Voltage Sensor

The next sensory device added was a tachometer to measure the revolutions per minute (RPM) of each motor. To construct a working tachometer, a Hall Effect sensor was used. Hall Effect sensors work by allowing a signal to pass through whenever a magnetic field is detected nearby [13]. By attaching a magnet to the shaft of each motor and aligning Hall Effect Sensors in their proximity, a digital signal can be captured each time one full rotation of the shaft occurs. By counting the number of instances of this phenomenon over a set period of time, the RPM can be calculated. A schematic of this circuit and the magnetic shaft design are shown in Figures 12 and 13.

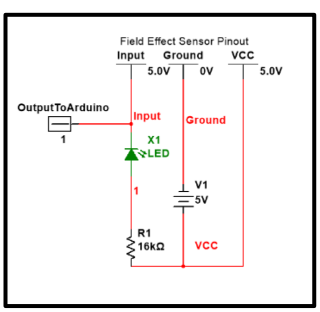

Fig. 12: Tachometer Schematic

Fig. 13: Magnet Installed on Coupling

All integrated sensors send their outputs to the Arduino Mega unit for collection and further data processing.

Graphical User Interface

To enhance the data collection, user interface, and control system of this project, a graphical user interface was added to the design. This GUI would aim to provide users with the ability to toggle power sources, control the behavior of the motors, and monitor/visualize the data collected from the Arduino Mega. Using MATLAB's App Design program, the following GUI in Figure 14 was conceived.

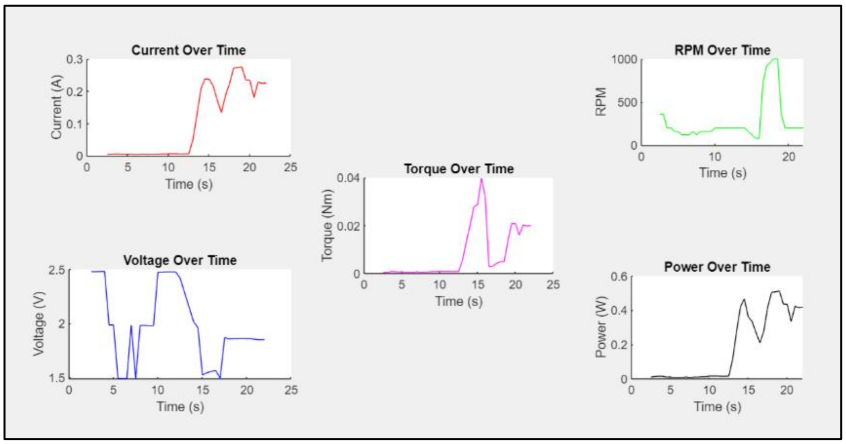

Fig. 14: GUI Design

The GUI would communicate with the Arduino Mega through a serial connection. The GUI would send information such as power source toggles, motor state settings, and PWM values to the Arduino over this serial connection. In return, the Arduino would periodically send voltage, current, and RPM values.

Designs are still ongoing for the overall structure of the vessel and to determine a method of fabrication. Since the focus of this project is on the intelligent power system itself, the boat structure is a low priority until other modules, such as the power system and sources, are fully ready for implementation. One component of the boat's structure is in development, however. To provide as efficient a load as possible, structures have been designed to provide shaft stabilization to the motors. This design aims to reduce oscillatory vibrations at high shaft speeds by implementing supports and bushings to mechanically inhibit motion in Figure 15.

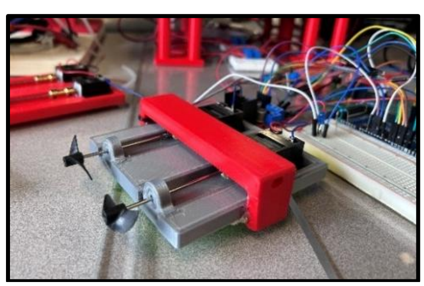
Fig. 15: Shaft Support Structure

Analysis of Power Source Performance

Data collection was conducted on the 10W hydrogen fuel cell with multiple Hydrostiks to determine the characteristics of the voltage and current delivered to the load of two motors wired in parallel. Voltage was measured directly across the fuel cell's leads, and current was calculated by measuring the voltage across a 0.01Ω shunt resistor wired in series with the motors. The graphs of voltage, calculated current, and power delivered are depicted below.

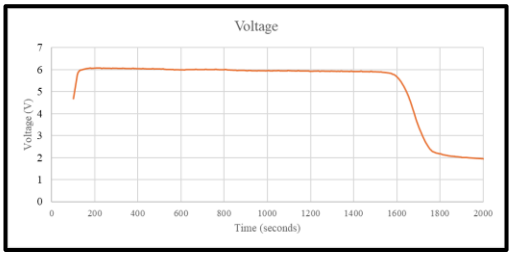

Fig. 16: Hydrogen Voltage Graph

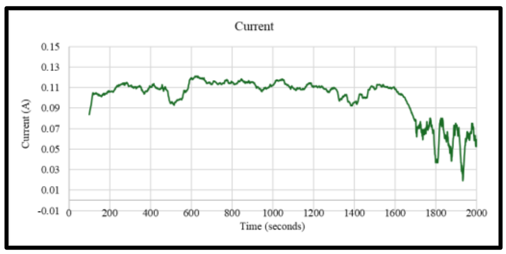

Fig. 17: Hydrogen Current Graph

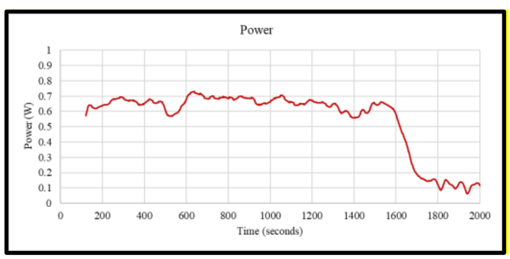

Fig. 18: Hydrogen Power Graph

Notably, the raw data was filtered after collection to remove outliers caused by collection errors and noise utilizing a moving average across 100 data points. This yielded a constant power supply of approximately 6V, 0.1A, and thus 0.6 W for 25 min. This yields an approximate 0.25 Wh capacity per hydrostik delivered to the load in this configuration. These output characteristics fall close to the maximum operational range of the selected motors and demonstrate their efficacy as a direct-drive or battery-replenishing power source at this scale.

Another experiment was conducted using a prototype of 4 solar panels, connected to a solar-tracking apparatus designed to maximize their solar exposure, pictured below.

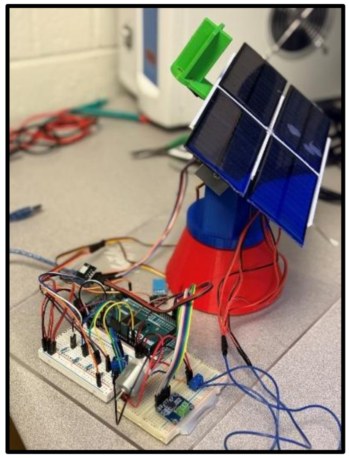

Fig. 19: Solar Panel Apparatus

The solar panels are powering a single DC motor. An INA219 sensor was used to gather voltage, current, and power data generated by the solar panels. Temperature and humidity data were gathered by a temperature/humidity module. The experiment started on a sunny afternoon, with a temperature of 28 F and 44% humidity, ending towards an altostratus cloud cover. Data was recorded via Arduino using Excel Data Streamer for a duration of 90 minutes. The graphs for voltage, current, and power generated by the solar panels are depicted below.

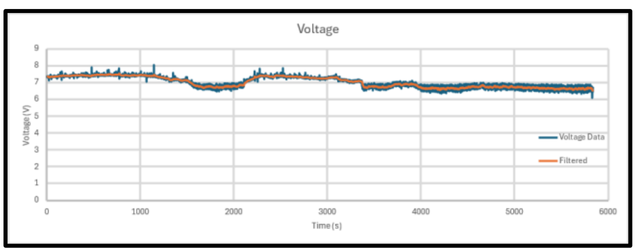

Fig. 20: Solar Panel Voltage Graph

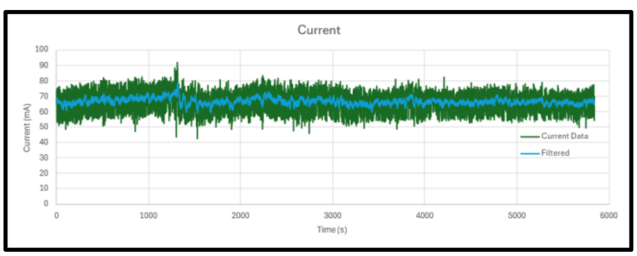

Fig. 21: Solar Panel Current Graph

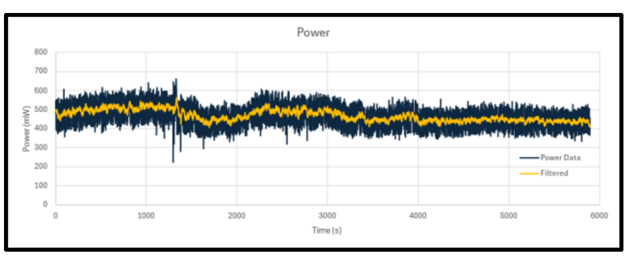

Fig. 22: Solar Panel Power Graph

Both raw and filtered data are depicted to show the collection errors and noise in the system. The 4 solar panels averaged at about 7 V, 0.7 A, and around 0.5 W for 90 minutes. This yields an approximate 0.33 Wh for 4 parallel solar panels. This proves solar panels are a viable power source for both the selected motors and for charging the batteries. For the final product, all 12 solar panels will be utilized to improve efficiency in charging the batteries and offer a more reliable source for direct drive power.

When measuring and monitoring the power delivered to the system's load, it is crucial to acknowledge and account for the losses throughout the system's wiring and circuit elements. In these experiments, the voltage and current were measured directly after the fuel cell or solar panels and thus provided a model of the best possible power delivery without accounting for inherent losses. When monitoring and modeling the final system's performance, sensors will be implemented directly across the motors as well as the sources to account for losses and maintain the most accurate data collection and representation.

The data collected in these experiments provides a critical basis for establishing this project's autonomous control system within the MATLAB GUI. When sensors are implemented into the final prototype, the system will contain code that references this library of data in order to determine power source performance and be able to accommodate load demands appropriately. The interface will additionally provide the user with a visual indication of the state of each power source, such as the battery charge level, solar panel performance, and time left in a single charged hydrogen storage device. Intimate familiarity with the discharge characteristics and capabilities of the power sources is necessary to fully optimize this system.

Conclusion

Within the maritime domain, the prospect of hydrogen power serving as the source of energy for a sizeable portion of the world's ships is increasingly changing from a possibility to a realizable solution. With the limitations of hydrogen energy in mind, it has become increasingly clear that such a power plant would rely on multiple sources to remain effective. Furthermore, such a system would require an 'intelligent' aspect that allows it to autonomously manage itself using modern computing techniques.

Thus far, the aim of this paper has been to gain a deeper understanding of the developing framework for hybrid hydrogen energy production. The phases outlined within this project set a clear vision for achieving a proof of concept for an intelligent hybrid power plant. The tangible strategies for this have been outlined with the system requirements and design.

The project has accomplished the deliverables for Phase I and is working through Phase II, constructing a basic controller that can toggle between sources. Such an achievement has allowed for data collection to occur, highlighting the behavior of the three power sources employed for this project. This has enabled a greater understanding of the power systems involved, as well as setting the path forward for autonomous control.

The work done thus far has set the foundation for the next phases of this project. As development continues, this project will move forward to gain a greater understanding of hybrid hydrogen technology and how it can be utilized to its fullest potential. The focus for the second semester will shift toward building a controller that can take in numerous inputs to allow for efficient decision-making. Such an endeavor will require the implementation of external sensors that consider factors like weather. Additionally, more work will be done to process the data from these sources as well as employing advanced computing techniques to uncover the patterns and behavior that define the collected results.

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