Hybrid Hydrogen Vessel Design

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Abstract

The United States Coast Guard regulates maritime vessels, including those equipped with hybrid hydrogen-powered propulsion systems and artificial intelligence (AI). The sponsor for this project is the USCG Marine Safety Center. The goal of this project is to create a small-scale hybrid power vessel that automatically switches between energy sources of hydrogen and batteries using both a traditionally coded algorithm and a machine learning algorithm. Hydrogen-powered vessels often use hybrid energy systems that store energy in batteries alongside hydrogen-generated power. This allows the vessel to draw power from multiple energy sources in different circumstances to most efficiently meet the load demand. Additionally, automatic transitions between energy sources allow for the maximization of efficiency and reduce the demand on the vessel crew. In highly complex systems in which large amounts of data can be collected, artificial intelligence systems show promise in improving efficiency. Therefore, this project will incorporate machine learning algorithms as testing progresses. The operational objectives that support the project goal are the design of a vessel hull, a propulsion system, an electrical power circuit, and an energy management algorithm; the simulation of these systems to verify their effectiveness, the construction of these systems, the integration of these systems into a single vessel, and the incorporation of a machine learning energy management algorithm.

This multidisciplinary project includes 5 students: two mechanical engineering majors to design and manufacture the vessel hull and propulsion system, two electrical engineering majors to design and manufacture the power circuit and algorithm, and a cyber systems major to collect data and design and create a machine learning power management algorithm. The vessel hull will be approximately 4.5 feet in length, 1.5 feet in width, and propelled using a 200-watt brushless motor propeller. The power circuit will supply and store energy via a 200-watt (W) hydrogen Proton Exchange Membrane (PEM) and two 6-volt, 7-amp-hour batteries. The circuit will be managed using an 8-module relay and an Arduino Mega. The data collected from testing the small-scale vessel with procedural code automation will be used to train the machine learning algorithm.

Background

In 2024, the *SEA CHANGE* became the first hydrogen fuel cell ferry to enter commercial service [1]. *SEA CHANGE* uses a proton exchange membrane fuel cell (PEMFC) and a battery system, including an automated method for switching between power sources. Demand for vessels with multi-source onboard energy systems like the *SEA CHANGE* is increasing, along with the need for power management strategies that preserve safe navigation, operational reliability, and mission endurance [2]. Hybrid hydrogen architectures provide operational advantages because batteries can support rapid load changes while fuel cells provide high-efficiency energy during steadier operating conditions, reducing fuel consumption and operating costs. A system that switches between these power sources must first decide if efficiency or responsiveness is more important, then switch sources to reflect that decision. Operating two different power sources optimized in different conditions can contribute to maximizing the overall operational efficiency and mission endurance of the system, making vessel operations more economically sound.

In a 2023 review of Scandinavian hybrid vessels by the Maritime University of Szczecin in Poland, the offshore patrol vessel Viking Lady was retrofitted with batteries and fuel cell technology in 2011 to supplement the diesel engines. With 450 kWh lithium-ion batteries and a 320 kW fuel cell integrated into the power system, fuel consumption was reduced by 10-17%, and engine operating hours decreased by 36% [3]. The review also includes 14 other vessels that have employed hybrid technology. This research indicates that hybrid battery and hydrogen technology demonstrate measurable reductions in fuel consumption and engine operating time while maintaining system performance.

The work builds upon a 2024 project that integrated batteries, hydrogen fuel cells, and solar to power a load with a MATLAB user interface [4]. This project's scope was to expand to a mobile vessel platform with propulsion, onboard sensing, and automated switching intended to support future regulatory insight for hybrid hydrogen vessels.

The recent performance of the *SEA CHANGE* demonstrates the operational characteristics of PEMFC-powered vessels. When a constant load is applied, a PEMFC is comparable in torque to a diesel system. However, a PEMFC performs poorly under highly variable loads, such as the throttle changes experienced on a vessel as it docks.

Vessels operating with hydrogen as their fuel source require a fuel cell to create an electrical current for their motors. In this project, a PEMFC will be used to convert chemical energy into electrical energy [5]. The PEM consists of an anode and a cathode, which are separated by an electrolyte. When hydrogen is brought to the anode, it splits into protons and electrons after interacting with a catalyst. The protons pass through the electrolyte, but the electrons take an alternate route. An external circuit harnesses the flow of electrons through this alternate route. With a constant flow of hydrogen into a PEMFC, a current is delivered to the motors through the power management system. This steady current flow makes hydrogen ideal for constant loading conditions, like propelling a vessel at its cruising speed [6].

Another class of onboard power sources that have great maritime capability is lithium-ion batteries [6]. The implementation of batteries can provide power during peak loading conditions when hydrogen fuel cells fall short. Battery storage systems also enable the use of onshore electricity when going into port frequently, as most passenger ferries do. While batteries may seem to be a great source of power for a running vessel, there are limitations for a system that only uses battery power [2]. A battery system acting as the principal power source would need to be recharged frequently, whether onshore or underway, limiting the vessel to only short transits. Recharging a battery system reduces the power system efficiency by about 15% because of additional energy losses incurred during battery charging, energy storage, and battery discharging. It would also require a large amount of space on board a vessel with limited cargo. When integrated with another power source, such as the hydrogen fuel cell, the lithium-ion batteries can supplement power demands when operating in dynamic conditions.

Integrating hydrogen fuel cells and lithium-ion batteries into a hybrid system can reap the benefits of both while mitigating the limitations of each [7]. In scenarios where a high responsiveness is the most desirable characteristic of the power system, lithium-ion batteries should be connected to the outputs (thruster and steering system). However, in long-distance cruising scenarios, or when batteries cannot provide sufficient power, the hydrogen fuel cell should be used to power the thruster to reduce energy loss in conversion processes. Furthermore, exigent circumstances such as a medical emergency onboard require maximum thrust possible, suggesting the need for the ability to combine multiple power sources to increase the vessel's maximum speed. In summary, implementing both a hydrogen PEMFC and lithium batteries with onboard dynamic power switching capabilities is expected to improve safety, operational efficiency, and systems performance under varying conditions for a hybrid hydrogen vessel.

Educational Objectives

This project is structured as an applied, multidisciplinary educational experience that directly connects undergraduate engineering students to real-world Coast Guard systems, stakeholders, and mission needs. Students work closely with the Marine Safety Center Electrical Branch, which conducts regulatory compliance reviews for commercial vessels, including the *SEA CHANGE*, the first hydrogen-powered ferry to enter commercial service in the United States. This connection grounds the project in authentic regulatory, safety, and engineering constraints rather than purely academic design goals.

From an educational perspective, students develop foundational and transferable expertise in hydrogen fuel cells, hybrid electric power systems, energy storage, power electronics, sensing and monitoring, and control algorithms. Electrical engineering students gain hands-on experience with power system architecture, relay-based switching, battery management systems, instrumentation, and embedded control. Mechanical engineering students focus on propulsion integration, vessel configuration, hydrodynamic loading considerations, and mechanical mounting and stability. The cyber systems student develops skills in data collection, feature selection, and machine learning applied to physical systems, reinforcing the connection between software, hardware, and operational behavior.

The project emphasizes engineering judgment under realistic constraints. Students must balance efficiency, responsiveness, safety, and reliability, mirroring decisions made in operational vessels. They engage with incomplete data, iterative testing, troubleshooting, and system integration challenges that closely resemble fleet engineering problems. This experience prepares students to serve effectively as Coast Guard engineers by building intuition for how novel power systems behave outside of idealized models.

In addition to immediate fleet relevance, the project provides strong preparation for postgraduate study and research in energy systems, controls, and alternative propulsion. By working on a hydrogen-based hybrid vessel with direct regulatory relevance, students develop both technical depth and professional context, positioning them to become subject-matter experts capable of supporting future Coast Guard acquisition, regulation, and operational decisions related to alternative fuels and advanced power systems.

Design Project Objectives

A vessel with two main sources (a 200 W hydrogen fuel cell and two 6 V batteries) requires an energy management system that selects and switches among allowable power configurations. The primary objective is to implement automatic power switching using procedural code and compare it to a machine learning-based approach. The comparison will identify weaknesses in threshold-based logic and determine whether data-driven methods better handle complex interactions.
To establish decision thresholds and training data, two foundational evaluations guide design:

1. Efficiency characterization under steady throttle conditions
2. Responsiveness characterization under rapid or repeated throttle changes

These evaluations support both the procedural switching thresholds and the supervised learning dataset labeling and feature selection.

Efficiency Test: The automated control system needs thresholds that trigger a switch. The first of these thresholds to be analyzed is efficiency. When a vessel is set at a constant speed over a prolonged period, it is essential to determine whether the fuel cell or the batteries provide more efficient power delivery in this setting. To test this, the desktop-sized vessel will be placed in a pool and run at low, medium, and high thrust relative to the thruster's capacity. For testing purposes, the hydrogen fuel cell voltage was stepped down to match the battery voltage such that the power sources were supplying the same amount of power to the circuit. Once the vessel reaches its commanded speed, the time it takes to cover a ten-foot distance will be measured and timed. An average velocity shall be computed for low, medium, and high thrusts for each power source. The average velocity of the vessel powered by the fuel cell will be compared to that of the battery-powered vessel. Thresholds will be written into the final code that identify low, medium, or high thrust for a prolonged time, and power sources will switch based on the efficiency test data. Specifically, if the vessel has not received a new throttle command within the last minute, then the most efficient power source will be selected.

Responsiveness Test: For ferries like the *SEA CHANGE*, which dock multiple times per day, another critical factor in the switching logic is the power system's responsiveness. The vessel needs to be able to maneuver quickly in close-quarter situations, requiring adequate response time. The responsiveness of both the 6 V batteries and the 200 W hydrogen fuel cell will be evaluated by measuring their step response to a commanded thruster RPM change. The step response will be plotted in Excel. The time constant (τ) will be determined graphically and used to compare which power source responds more quickly to a commanded change in speed. Thresholds will be programmed into the procedural code to detect significant or consecutive throttle commands, allowing the system to identify when a more responsive power source is required.

Procedural Code: Procedural code will be the first of two methods to be compared and analyzed to accomplish the goal of having automated power source switching within the power system, as shown in Figure 1. Advantages of procedural code include its predictability in terms of being user-defined throughout the process and based on well-known interactions. This also makes the testing process much simpler, as the system's response is more deterministic, meaning the same inputs will always give the same outputs. To switch between different sources based on the inputs, numerous different "if-then" statements are used. An example of this would be something as simple as: "if efficiency rating is less than X then switch", with "X" being an input value determined based on tests run over time. These "X" values will be based on thresholds according to observations and data recordings from sensors that are installed within the system. The straightforward logic of procedural code automates the power system, but only to a certain extent. Numerous outputs resulting from the system may not be observable due to the dynamic interactions of the inputs and other factors that may be completely imperceptible.

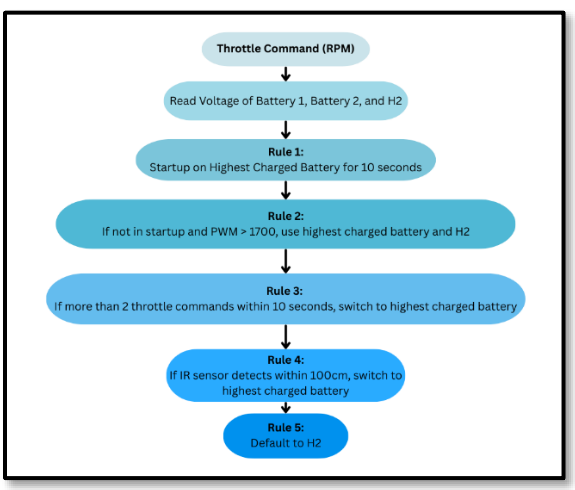

Figure 1. Procedural Code Schematic

AI Implementation: AI, specifically machine learning, will be utilized to recommend power mode selection based on observed system state and operating conditions. Rather than manually defining thresholds, the model learns patterns from data that include throttle commands or, in this case, the integrated power modes, RPM response, source voltages and currents, battery state estimates, and hydrogen usage indicators. The initial training dataset will be drawn from MATLAB simulations of the power system and expanded with real vessel trial data. MATLAB machine learning and statistical learning tools will be used to build and validate the model [8]. As additional data are collected across operating conditions, the model can be retrained to improve robustness and to capture interactions that are difficult to encode procedurally.

Project Phases

Given these objectives, the project is split into five phases. Phase 1: Design an advanced relay that switches between the 200W fuel cell and the 6 V batteries based on the identified thresholds. Phase 2: Test the responsiveness and efficiency of each power source on the vessel. Phase 3: Construct the automated power management system on a vessel where procedural code is utilized. Phase 4: Collect sufficient quality training data for artificial intelligence integration. Phase 5: Compare the performance of the system using artificial intelligence to that of procedural code.

System Design

The system design highlights the conceptual basis for powering an underwater thruster with multiple power-source arrangements, as well as the hardware required to deliver each arrangement. The final form of this project will be a functional vessel with a hybrid power system. To meet its required goals, it will consist of a seaworthy small craft that maneuvers in the water, a remote control system that receives commands from a user, a series of power sources (specifically hydrogen fuel cells and two battery cells) to provide hybrid energy, and an intelligent control system to automatically manage power sources. Thus, the final design would need to consist of four main components:

i. Hybrid power sources with switching capabilities
ii. Charging capabilities for batteries in standby
iii. Intelligent power control system
iv. Seaworthy structure with propulsion and steering system

Figure 2 depicts the system diagram demonstrating the interactions between these four components, as well as ancillary components that are required for their interconnection.

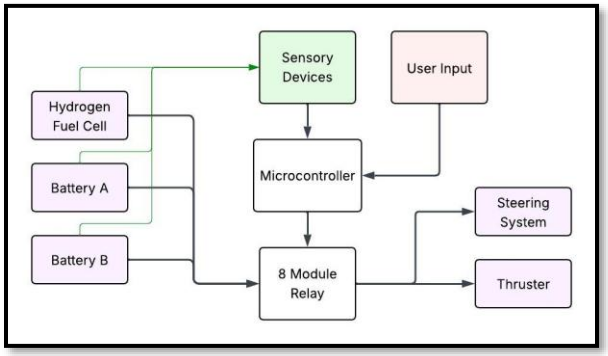

Figure 2. System Design

This system diagram shows that the power controller will have the choice of power at any given time between the hydrogen fuel cell or either battery. The power controller will consist of a microcontroller (Arduino Mega) and an eight-module relay. Power sources will supply the outputs (propeller and rudder) through the electrical connections as determined by the relay. The microcontroller will make decisions about which power sources to draw from based on both the user demands and the onboard sensors. The entire electrical system was designed for implementation on a functional small-scale vessel. The system was fitted onto a 4.5-foot Styrofoam hull and tested under loaded conditions in a controlled pool. The current implementation of the system on the small-scale vessel is shown below in Figure 3.

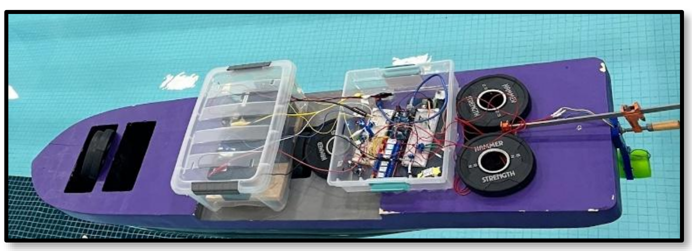
Figure 3. Implementation of Power System on Vessel

Hybrid Power Sources

The hydrogen fuel cell will be one of the primary sources for power on this vessel. Due to the nature of the PEM, it has a longer settling time after shifts in its electrical load. The fuel cell will perform far better at supplying electrical power in less dynamic conditions where the desired steady state remains relatively constant. From testing, the hydrogen fuel cell produces 14-16 V of electric potential. The 200 W hydrogen fuel cell uses small canisters of compressed hydrogen (Hydrostik Pro), shown in Figure 4. This system uses the Hydrostik Pro for its safety and ease of refilling the canister. Due to the educational nature of this project, it is important to have a system that is easily reusable for a low cost, allowing for rapid testing and continued iteration. Upon testing the Hydrostik's compatibility with the fuel cell, it was found that each stick provides approximately 10 minutes of run time to the 200 W fuel cell before hydrogen is depleted. The battery cells shown in Figure 5 are two 6.4 V lithium-polymer batteries. These were chosen because of their availability and maximum voltage capacities.

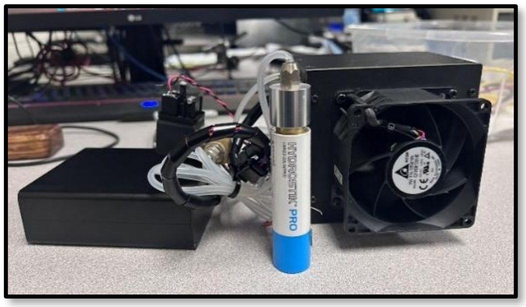

Figure 4. 200W Hydrogen Fuel Cell and Hydrostik Pro

Figure 5. Lithium-Ion Battery

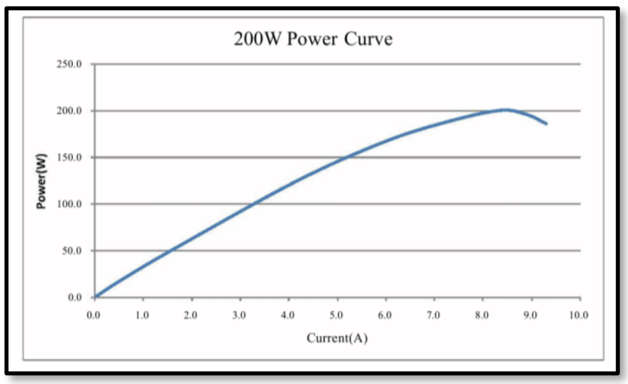

Figure 6. Power Curve for 200W Fuel Cell [9]

The PEMFC has a roughly linear power curve, demonstrating that the fuel cell increases its power output until reaching a maximum of 8.2 A, as shown in Figure 6 [9]. However, its desired output will never exceed 2 A in this project, with the initial setpoint at 15 V and 0-1.5 A depending on the desired throttle. Meanwhile, the initial setpoints for the battery are its nominal voltage of 6 V, outputting a power of 0-1.5 A, also depending on the desired throttle. During transitions between the active power source, diodes are used for power matching to ensure smooth shifts without drops in power.

An eight-module relay handles a switch to connect the power sources. A relay is an electrical module that takes a high or low electrical signal and closes or opens an electrical connection accordingly. A relay uses an inductor to create a magnetic field when active to physically rearrange the electrical connections based on the input. Each relay module has a common node, the node to which it is normally closed (NC), and the node to which it connects only when energized (NO). A relay was chosen for the power controller system because it will allow the microcontroller to rearrange the electrical connections as needed at any given moment. Additionally, the microcontroller will be electrically isolated from the power sources themselves, protecting it from the high voltages carried on the power rails. This system uses an eight-module 5 V relay from HiLetGo. This was chosen because it is robust and includes internal safeguards against power surges.

The main mechanical power output of the vessel will be a waterproof brushless underwater thruster DC motor with a propeller attachment, as shown in Figure 7. It can be powered up to 24 V and 20 A, with a maximum power rating of 200 W. A thruster mount was designed by students to hold the thruster and included screw holes for drilling into the boat, as shown in Figure 8. There were some difficulties drilling into the foam, so a clamp was used to hold the mount in place. This was not ideal, and there will be further design iterations in the future.

Figure 7. Brushless Underwater Thruster

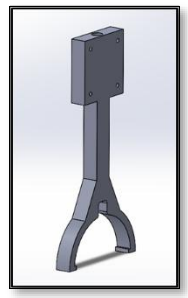

Figure 8. Thruster Arm Mount

A Hall-effect sensor is a magnetic-field detector, as shown in Figure 9. It senses the presence of a magnetic field and produces a corresponding electrical signal [10]. The sensor typically has three pins: one for ground (GND), one for the supply voltage (VCC), and one for the signal output, which can be connected to a microcontroller such as an Arduino. When a magnet is mounted on a rotating thruster, the Hall effect sensor can detect the passing magnet with each rotation, producing a pulse that corresponds to the rotational speed (RPMs).

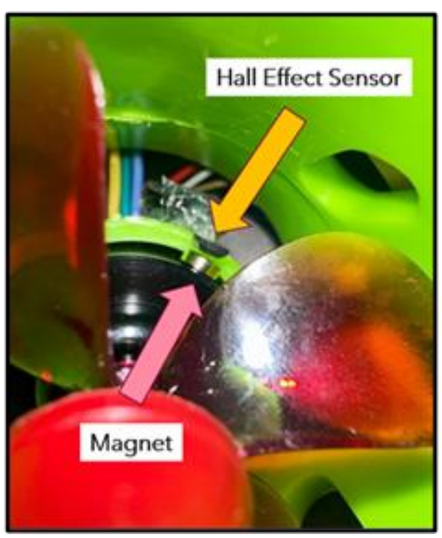

Figure 9. Hall Effect Sensor Installed on Thruster

Battery Management and Power Modes

The vessel is equipped with two batteries for power selection. A battery management system (BMS) regulates the charging of one or more batteries. The first requirement of the BMS is to facilitate the safe charging of the batteries. The vessel used lithium-iron phosphate ($LiFePO4$) batteries. All batteries based on lithium-ion have a risk of thermal runaway or failure if overcharged. It was also critical that batteries were connected to the BMS in a way that did not allow a short circuit between nodes of different voltage levels, which would cause a surge of current that would likely damage batteries or any connected equipment. The BMS was first used to experimentally charge a battery with a power bank, set to power levels similar to those of the hydrogen fuel cell. After this simulation proved successful, the BMS was tested with the active 200 W hydrogen fuel cell, which was successful after troubleshooting. Future stages of this project will integrate the BMS into the automatic relay control, to allow the hydrogen fuel cell to recharge the battery that is in standby status.

All power sources were connected to the output electrical rail through the 8-module electromechanical relay. This was chosen because it handles high currents well, costs less than a solid-state relay, and can physically disconnect electrical nodes to minimize the opportunities for short circuits between high-voltage power sources. The circuit was connected to the relay to allow for a limited number of configurations, and the microcontroller was programmed to follow the same restrictions. These options were encapsulated in the following five “Power Modes”, describing the set of possible power configurations the system may choose from at any given time.

Power Mode 1: This mode connects battery A directly to the output, providing a highly responsive power source for scenarios such as docking and precision maneuvering, as shown in Figure 10. It also allows for the charging of battery B from the hydrogen fuel cell, should the system desire.

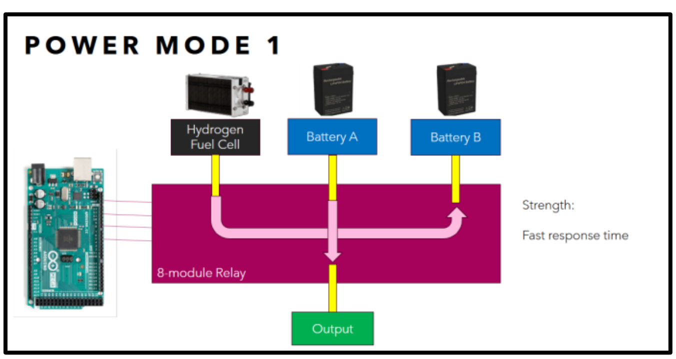

Figure 10. Power Mode 1

Power Mode 2: This mode connects battery B directly to the output, providing the same benefits as Power Mode 1, as shown in Figure 11.

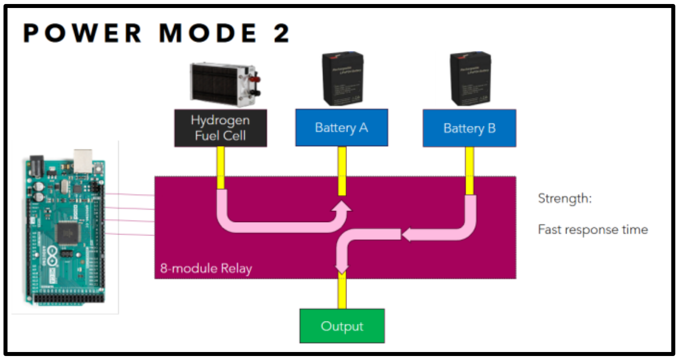

Figure 11. Power Mode 2

Power Mode 3: This mode, shown in Figure 12, represents the configuration that connects the hydrogen fuel cell directly to the output electrical rail. This allows for the most efficient use of energy since there are no conversion losses through the BMS. Additionally, Power Mode 3 allows charging either battery.

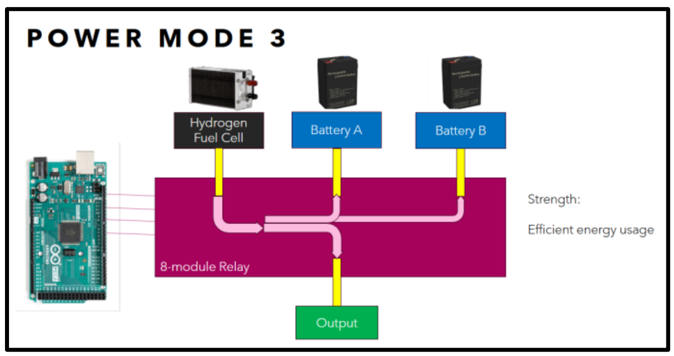

Figure 12. Power Mode 3

Power Mode 4: This mode, shown in Figure 13, operates a relay referred to as the “bump” relay, which connects Battery A in series with the hydrogen fuel cell. This allows for the maximum possible thrust.

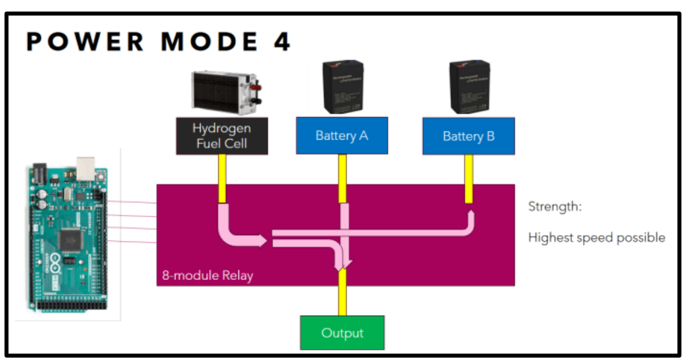

Figure 13. Power Mode 4

Power Mode 5: This mode utilizes battery B in series with the hydrogen fuel cell, creating the same options for maximum thrust at a high energy cost. Both Power Mode 4 and Power Mode 5 allow for the recharging of the respective batteries not in use, as shown in Figure 14.

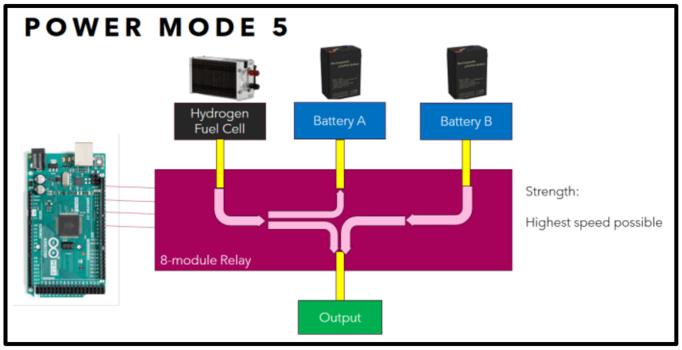

Figure 14. Power Mode 5

The final program is designed to weigh all input values from designated sensors and continuously determine which of the 5 Power Modes to use in each moment. The infrastructure of the programmable microcontroller interface with the 8-module relay will allow for dynamic switching while enforcing safeguards that prevent unintended short circuits.

Conclusion

This project serves as an applied educational experience that directly connects undergraduate engineering students with real Coast Guard systems, stakeholders, and mission needs through collaboration with the Marine Safety Center Electrical Branch, which conducts regulatory compliance reviews for commercial vessels, including the *SEA CHANGE*, the first hydrogen-powered ferry in U.S. commercial service. Students build foundational expertise in hydrogen fuel cells, hybrid power systems, energy storage, power monitoring, and control, while working within realistic safety, regulatory, and operational constraints. The project emphasizes hands-on system integration, testing, and engineering decision-making that closely mirrors fleet engineering challenges, directly preparing students to serve effectively as Coast Guard engineers. At the same time, it provides strong preparation for postgraduate study in energy systems, controls, and alternative propulsion, helping develop future technical experts in emerging maritime power technologies.

The current prototype of the small desk-sized vessel successfully runs the thruster off all five power modes out of water. This is considered the system's no-load condition. The vessel was also tested inside a pool and ran successfully under all five power modes. This is considered the system's load condition.

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