Spring Term Report

Fuel cell integration for the long-range long-endurance AUV LoLo

by

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List of Acronyms and Abbreviations

ADC Analog-to-Digital Converter.

AFC Alkaline Fuel Cell.

AI Artificial Intelligence.

ASR Area Specific Resistance.

AUV Autonomous Underwater Vehicle.

AV Autonomous Vehicle.

B Battery.

BMS Battery Management System.

CAN Controller Area Network.

CVM Cell Voltage Monitor.

DMFC Direct Methanol Fuel Cell.

DP Dynamic Programming.

ECMS Equivalent Consumption Minimization Strategy.

EMS Energy Management System.

FC Fuel Cell.

FCU Fuel Cell Control Unit.

FESS Flywheel Energy Storage System.

FMV Försvarets Materielverk.

GDL Gas Diffusion Layer.

HPS Hybrid Propulsion System.

I/O Input/Output.

KTH Royal Institute of Technology.

Li-ion Lithium-ion.

$LiFePO_4$ Lithium Iron Phosphate.

LiU Linköpings Universitet.

LoLo Long-range Long-Endurance maritime robot.

MAVLink Micro Air Vehicle Link.

MCFC Molten Carbonate Fuel Cell.

MPC Model Predictive Control.

NC Normally Closed.

PAFC Phosphoric Acid Fuel Cell.

PEFC Polymer Electrolyte Fuel Cell.

PEMFC Proton Exchange Membrane Fuel Cell.

RL Reinforcement Learning.

RTOS Real-Time Operating System.

SLIP Serial Line Internet Protocol.

SMaRC Swedish Maritime Robotics Centre.

SOC State Of Charge.

SOFC Solid Oxide Fuel Cell.

SOTA State-of-the-art.

TIA Telecommunication Industry Association.

UART Universal Asynchronous Receiver/Transmitter.

UC Ultracapacitor.

1 Introduction

Autonomous Vehicles (AVs) are becoming an increasingly integral part of modern society, with various levels of autonomy now embedded across land, air, and sea-based systems. While the spotlight has largely focused on self-driving cars and aerial drones, Autonomous Underwater Vehicles (AUVs) have also undergone significant development. These vehicles can have a great impact in marine applications such as environmental monitoring, underwater infrastructure inspection, and defense operations. [1, p. 41] [2, p. 451]

As AUVs are tasked with more complex missions in remote and challenging environments, the need for enhanced endurance, reliability, and energy efficiency becomes critical. This demand is driving a shift toward hybrid AUV systems that integrate multiple propulsion methods and energy sources to maximize operational flexibility. An important aspect of this transition is the adoption of hybrid energy systems, particularly those that combine high-specific-power energy storage with Fuel Cells (FCs). These technologies offer not only extended mission duration but can also reduce environmental impact and improve performance in deep-sea or long-range applications.[3, 4]

Within this context, the Swedish Maritime Robotics Centre (SMaRC) plays a role in advancing the development of next-generation intelligent underwater systems through close collaboration between academia and industry. Its research encompasses autonomy, endurance, perception, and communication, aiming to develop next-generation maritime robotics for ocean exploration, societal safety, and environmental monitoring [5].

1.1 Project description

As part of SMaRC's efforts to advance underwater robotics, this project focuses on the design, development, and integration of a Hybrid Propulsion System (HPS). The system combines a hydrogen FC and a rechargeable energy storage system into one of their AUVs, the Long-range Long-Endurance maritime robot (LoLo). Conducted as part of the Mechatronics capstone course at Royal Institute of Technology (KTH), this project covers the complete development process. This technical report outlines the project, covering the pre-study, design specifications, and the integration of a HPS into the submerged environment of the AUV LoLo. It aims to serve as a comprehensive documentation of the design and development process, providing a solid foundation for the continued development of the LoLo and similar systems. It is also intended to support future student teams tackling similar challenges, such as FC integration, control architecture, and system simulation.

The scope of the report covers hardware selection and layout, control system architecture, system modeling using Simulink, communication protocols, safety considerations, and integration of the system into a pressurized environment. The interdisciplinary nature of this work spans mechanical design, electronics, software development, and systems engineering.

1.2 Goal

The primary goal of this student project is to demonstrate the functionality of an integrated FC-HPS within the LoLo through a wet run. Through this wet run, the team aims to validate the hybrid system's functionality in a submerged environment.

1.3 Stakeholders

The core stakeholder in this project is SMaRC, with our main contacts being Niklas Rolleberg from the KTH Department of Aerospace, Mobility and Naval Architecture, and Clemens Deutsch, a postdoctoral researcher at SMaRC.

In addition, several other parties are involved in the development of the HPS and are relying on the results of this project. A key collaborator is Björn Eriksson from KTH Department of Applied Electrochemistry, who contributes with his expertise in FC technology and battery cell chemistry. Björn Eriksson also serves as the project manager for this project and represents it to additional stakeholders, including Försvarets Materielverk (FMV), which provides funding for the project.

1.4 Organisation

During the spring term, the seven-member project team, including a designated team manager, was divided into three subgroups. The subgroups focused on one subsystem each, i.e, the FC, rechargeable energy storage system, and Energy Management System (EMS). Each group leads research and design efforts within their domain, covering simulations, hardware/electronics, integration, and safety management.

The team meets bi-weekly with stakeholders and regularly with the project coaches of the KTH Mechatronics division to align on progress, direction, and scope. To streamline communication, a dedicated Discord channel is established for ongoing collaboration between the team and key stakeholders. The project, encompassing all subsystem teams, employs a prototype-oriented Life-Cycle Model based on an iterative approach. This spring semester report version concentrates on the pre-project phase, which includes problem analysis, system specification identification, and project plan formulation. Additionally, it outlines the initial stages of the main project phase, including the development of a system and subsystem concept and component integration. See Appendix A for the project plan. [6, pp. 33]

1.5 Requirements

The key requirements of the project are derived from the input of the stakeholders and the technical constraints. These requirements serve as essential design guidelines and form the foundation for validation and verification of the final system. The full list of requirements, with detailed descriptions, can be found in Appendix B together with associated delimitations.

2 Theoretical Background

The development platform, LoLo, in the scope of this technical report, shall be improved to achieve a greater range. Currently, batteries are utilized. This system is replaced with a hybrid Proton Exchange Membrane Fuel Cell (PEMFC) propulsion system to augment the specific energy density and therefore also the system's range and facilitate greater mission flexibility. This chapter presents the current state-of-the-art of FC systems in submarines and the theoretical background needed for this project. This includes the PEMFC and HPSs. Furthermore it looks at existing approaches for energy-management in a HPS and existing FC-powered submarines.

2.1 Fuel Cell

Fossil fuels are depleting and polluting, contributing to global warming and energy insecurity. As a result, sustainable alternatives like FCs are gaining momentum [7, p. 621]. The technology of FC itself was first discovered by Sir Willian Grove in 1839 and later described as a "gaseous voltaic battery" [8, p. 296]. The term FC was introduced by Mond & Langer half a century later. [7, p. 621]

$$2\,H_2 + O_2 \rightarrow 2\,H_2O \tag{2.1}$$

FCs convert chemical energy from a fuel (e.g., gaseous hydrogen) and an oxidizing agent (e.g., gaseous oxygen) directly into electrical energy, resulting in a high efficiency and clean solution due to low chemical, thermal, and carbon dioxide emissions. The byproducts are heat and water (see equation 2.1). Comparing the FC to combustion or heat engines, it is clear that the FC does not need several intermediate steps of producing heat and mechanical work to generate electical power. These conversion steps are typical for conventional power generation methods (e.g. chemical energy - fuel → internal energy - heat → transfer internal energy onto a working medium, e.g. water → achieve useful work from a circular process → electric current). The maximum electrical work that can be extracted from a FC during constant temperature and pressure is given by the negative of the Gibbs free-energy difference, which provides a thermodynamic limitation similar to the Carnot efficiency for heat engines [9, p. 40]. High theoretical efficiencies (between 83% [10, p. 34] and 95% [11, p. 13]) can be achieved. [12, p. 1-1]

There are mainly the following types of FCs: PEMFC alias Polymer Electrolyte Fuel Cell (PEFC), Direct Methanol Fuel Cells (DMFCs), Solid Oxide Fuel Cells (SOFCs), Molten Carbonate Fuel Cells (MCFCs), Phosphoric Acid Fuel Cells (PAFCs) and Alkaline Fuel Cells (AFCs). In this report, the focus is on the PEMFC due to its low operating temperature, low noise, quick start-up capability, light mass, high power density, longevity, as well as living up to the dynamic requirements of a mobility application, like in the given submarine use-case [11, p. 9]. In this report, the term "FC" refers specifically to the PEMFC. [7, p. 621]

In the FC electric energy is achieved by supplying hydrogen to the anode and oxygen to the cathode. Hydrogen gas passes through the Gas Diffusion Layer (GDL) to the catalyst surface. Here it is oxidized to protons (or hydrogen ions) according to Equation 2.2, which are ionically conducted through the polymer membrane (e.g Nafion). Since the membrane is an electronic insulator, the electrons instead flow through the electric circuit (see Figure 2.1).

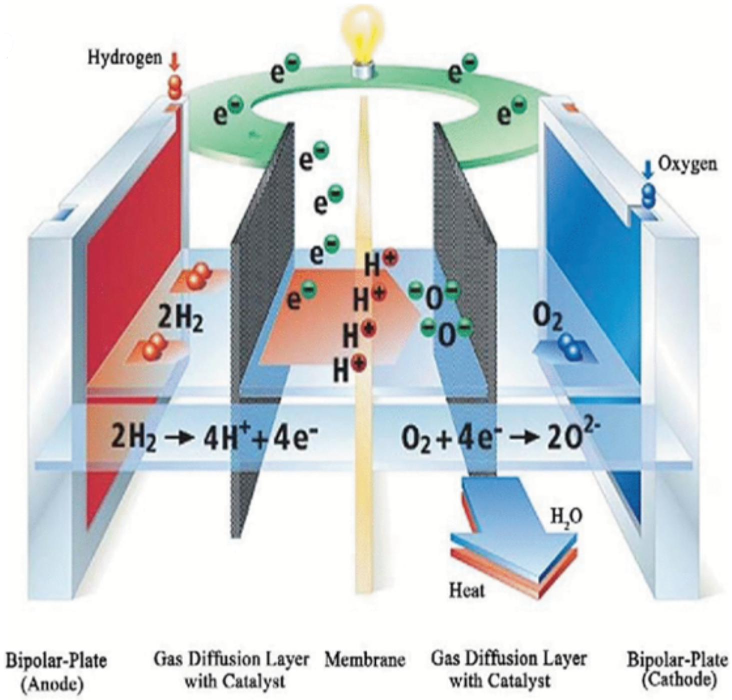

Figure 2.1: working principle of a PEMFC [13, p. 1033]

Oxygen enters the cathode and reacts with the electrons ($2\,e^{-}$) that moved from the anode to the cathode via an external electrical circuit (see equation 2.3) and the protons ($2H^{+}$) which migrated through the membrane to form water. The electrical circuit is closed and therefore showcases an electrical voltage source. A single FC's operating voltage is between 0.4 V and 0.85 V [14, p. 26]. The ideal voltage is 1.17 V (at 80°C) - theoretically 1.23 V [12, p. 2-6]. This cell potential cannot be reached in the real world due to irreversible activation-, ohmic-, and concentration-losses (see Appendix C).

$$\mathrm{H_2} \rightarrow 2\,\mathrm{H^+} + 2\,\mathrm{e^-} \tag{2.2}$$

$$\frac{1}{2}\mathrm{O_2} + 2\,\mathrm{e^-} + 2\,\mathrm{H^+} \rightarrow \mathrm{H_2O} \tag{2.3}$$

For most real world FC applications, unit cells are connected in a modular approach called a cell stack. This enables voltage and power output levels required for the given application. In the further chapter the abbreviation FC is often connected to the FC Stack and not the single cell. The connection between cells is often achieved with bipolar plates. They provide an electrical series connection and a gas barrier that separates fuel and oxidants of adjacent cells, as well as distribute the gas flow over the cells. Further channels for the coolant fluid enable the thermal management of the FC. The design of the Bipolar-plates, teflon mask, gas diffusion backings, catalyzed coated membrane affect the performance of the FC system. Besides the physical limitations of the systems, the performance, including the efficiency of a FC system, depend on the effective system control. To improve the electrochemical reactions in the stack, the humidity and flow rate of hydrogen and air, as well as the stack temperature need to be at their optimum. A further challenge is to prevent fuel starvation, ensure a safe and material friendly operation of the FC system. Further, the stack voltage can drop due to varying loads which need to be buffered by some form of short term energy storage for stability reasons. [12, p. 1-4, pp. 3-2] [15, p. 625]

For the integration of a FC system into a specific application, two main integration principles of driving the FC can be used: **Conventional** or **Air-Breathing** FC system.
A conventional FC uses compressors and flow controllers to transport the oxidant (air or oxygen) from the storage tanks to the active area of the FC through forced convection, while an air-breathing FC uses natural convection to transport the oxidant (ambient air) to the active area of the FC through an open cathode [16, p. 1]. In terms of AUV application, the conventional system approach is the most common one (see Section 2.5), and a possible reason for this could be the performance.

Calili-Cankir et al. [16] developed two mathematical models for a conventional and air-breathing FCs based on steady-state conditions and found that the conventional FC has a higher cell voltage and less ohmic and activation losses (see Appendix C) for the same current density compared to the air-breathing model. However, air-breathing models are simpler as a result of relying on natural convection of the oxidant, but the lower complexity does not compensate enough for the lower output power and lower operational stability [17, p. 105]. Similarly to Calili-Cankir et al. [16], Abdulrahman et al. [18] also developed two mathematical models for a conventional and an air-breathing FC, which showed that the conventional model outperformed the air-breathing model at higher current densities in terms of cell voltage. Furthermore, the study also performed a Taguchi analysis to identifying which design parameters had the greatest impact on performance. The result showed that the performance of both the conventional and the air-breathing FC could be increased by, for instance, reducing the cathode GDL thickness and increasing its porosity.

While FCs provide an efficient and clean energy source, its low specific power necessitates integration with auxiliary storage systems. The next section explores options for energy storage to complement FCs in hybrid propulsion.

2.2 Energy Storage for Hybrid Propulsion Systems

Due to the high specific energy and clean byproducts, FC-based propulsion systems serve as a feasible alternative to vehicle propulsion systems based on fossil fuels. However, using only a FC as a single energy source is often not feasible for delivering the required power to motors, as it has low specific power (see Section 2.1). Therefore, the FC is often paired with a Battery (B) and/or Ultracapacitors (UCs) in a hybrid system to create an energy buffer in parallel with the load and the FC itself to accommodate high dynamic loads. [19, pp. 254-255]

Choosing which auxiliary energy storage elements to combine with a FC depends on the characteristics of the vehicle in which the hybrid system will be implemented in. A combination of a FC and batteries provides a solution with high energy density, which is suitable for applications requiring long operating times. However, if the vehicle needs to cope with sudden high power demands, a combination of FC + UC or FC + B + UC would be a more feasible solution to increase the vehicle's power density. [20, p. 4265]

An alternative to UCs in terms of high specific power are flywheels. These energy storing components typically consists of a high strength carbon fiber wheel, magnet floating bearing supporting device, a motor/generator, and a power electronic control device. With fast charge/discharge capabilities and a specific energy approximate to a lead acid battery (40 Wh/kg), flywheels serves as a more flexible option compared to UCs in terms of design and operation. [21, pp. 22] One of the main purposes of using a Flywheel Energy Storage System (FESS) in a vehicle is regenerative braking. During this process, the flywheel stores some of the vehicle's kinetic energy (as rotational energy) that would otherwise be wasted as heat. [22, p. 482] However, if the vehicle type does not allow for regenerative braking, e.g in an AUV, the flywheel would mainly be utilized as an auxiliary energy storing element to provide high discharge rates. The reason for this is that it may not be possible to place the flywheel on the motor shaft, which limits the flywheel's capabilities. In that case, an UC would be more preferable due to its higher specific power. A set of different auxiliary energy storing components along with their specific power and energy is shown in Figure 2.2 down below.

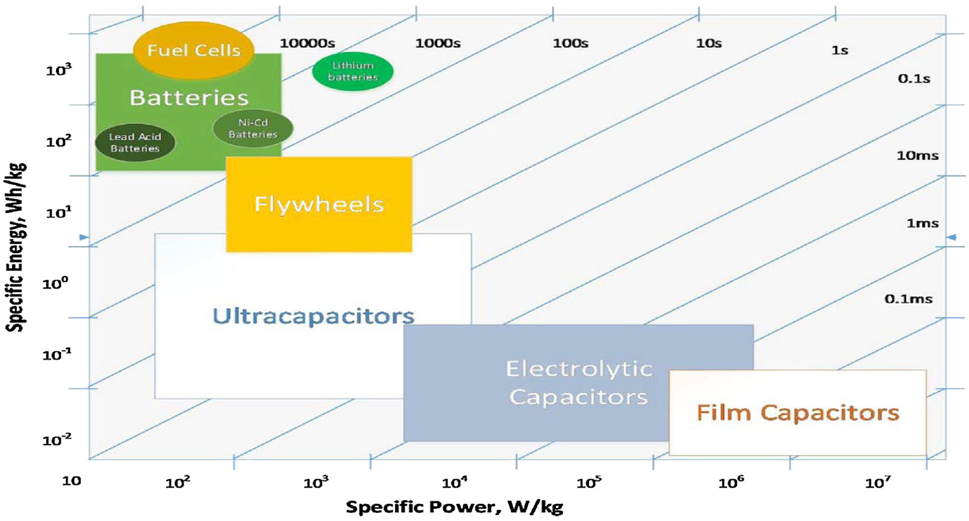

Figure 2.2: Specific energy against specific power of different energy storing components [20, p. 4268]

To make effective use of a hybrid energy architecture, a suitable control system is essential. The following section outlines energy management strategies for coordinating FCs and energy storage systems in hybrid vehicles.

2.3 Energy Management Systems for Hybrid Vehicles

The purpose of an EMS is coordinating the power distribution between multiple energy sources in a HPS, such as FCs, batteries, and UCs. An EMS is as such typically placed as shown in Figure 2.3, so that it can manage the operation of the Fuel Cell Control Unit (FCU) and Battery Management System (BMS) simultaneously [23, p. 1388]. The primary objective of an EMS is to optimize the vehicle's energy usage, thereby improving overall efficiency. Secondary objectives typically include minimizing fuel consumption, maximizing component lifespan, ensuring robust performance across diverse operational scenarios, or minimizing emissions [24, pp 32] [20, pp. 4263–4264], [19, p. 252], [23, pp. 1380–1381].

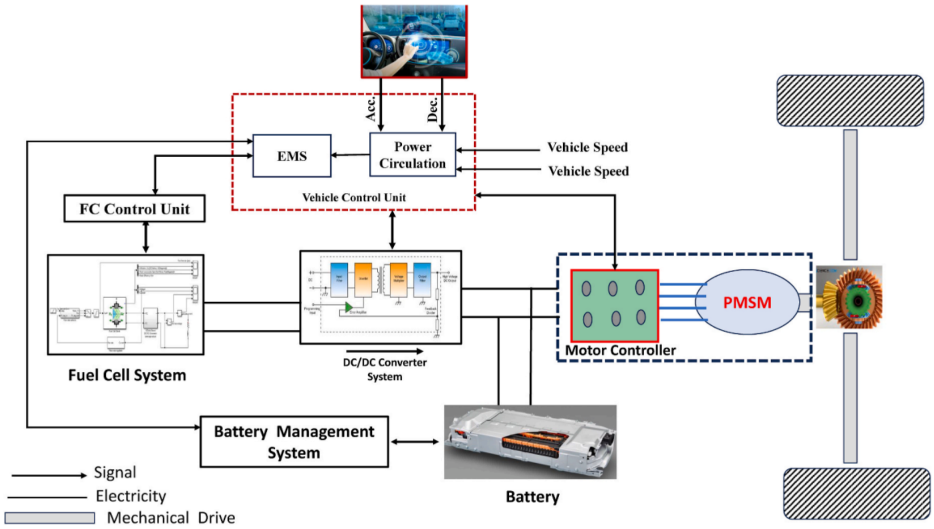

Figure 2.3: Typical HV topology found in [23, p. 1388]

EMS strategies are broadly classified into three main categories: rule-based, optimization-based, and Artificial Intelligence (AI) Deep Learning -based approaches, all of which can be further classified into online and offline methods [23, pp. 1382–1384], [25, pp. 191–193]. A chart showing the main categories and what methods belong to it can be found in Appendix D.

Rule-based methods include deterministic and fuzzy logic strategies. Deterministic rule-based methods utilize look-up tables and simple if-then control rules. These are easy to implement and computationally inexpensive but are limited in flexibility and adaptability to varying driving conditions , [19, pp. 252–253]. Fuzzy rule-based controllers, inspired by human reasoning under uncertainty, introduce more adaptability, but require extensive tuning and expert knowledge [26, p.4].

Optimization-based methods address EMS as a multi-objective problem where fuel efficiency, emissions, and component wear are considered. These can be divided into global and real-time strategies. Global optimization approaches, such as Dynamic Programming (DP) and optimal control, require knowledge of the full drive cycle, limiting their practical use in real-time applications [27, pp. 84–85], [19, p. 253]. Real-time strategies such as the Equivalent Consumption Minimization Strategy (ECMS) approximate the global optimum without full knowledge of future demands, achieving better practicality but with some loss of optimality [25, pp. 194–195].

AI-based methods, including Reinforcement Learning (RL), neural networks, and other data-driven models, are increasingly being adopted for EMSs due to their ability to model and learn complex, nonlinear dynamics. These methods can continuously improve their decision-making policies by interacting with their environment, making them suitable for real-time applications and adaptive control [23, pp. 1385–1389]. However, challenges such as the need for extensive training data, stability of learning, and computational overhead remain significant barriers to deployment in commercial systems.

Although EMS strategies have been extensively studied for ground vehicles, AUVs pose unique challenges. These are discussed in the next section.

2.4 Energy Management for Hybrid Propulsion in Unmanned/Autonomous Vessels

In the context of AVs, especially maritime systems like AUVs, the implementation of an EMS must consider additional challenges such as long-duration missions, uncertain sea states, and full autonomy with no human oversight. These conditions demand not only efficient energy allocation but also fault tolerance and adaptability to external and internal uncertainties [19, p. 253].

Rule-based strategies remain attractive for their simplicity and real-time applicability. However, their performance deteriorates in highly dynamic or uncertain environments due to their static nature. For instance, thermostat control or state-machine logic may fail to optimize fuel consumption or battery usage over longer missions [27, pp. 84–85].

Optimization-based strategies improve energy efficiency by using cost functions that account for mission profiles, power demand forecasts, and component health. These are particularly useful when a priori knowledge of the mission is available. However, they can be computationally demanding and less adaptable to unforeseen conditions, which limits their utility in truly autonomous settings [25, pp. 198–200], [20, pp. 4269–4271]. To understand how the discussed systems apply in practice, the next section reviews AUVs that use FC and HPS.

2.5 Collection of existing FC-powered AUVs

Whilst only a few FC-powered AUVs are publicly known to exist, this chapter provide a reference on how a collection of those was implemented in the power system.

2.5.1 Urashima

Urashima is an AUV from the Japanese Agency for Marine-Earth Science and Technology [28, p. 1]. It uses two PEFCs with a combined power output of 4 kW. The required hydrogen is stored in an AB5-type metal hydride. It absorbs hydrogen below 0°C, stores it at 25°C, and releases it at temperatures above 50°C. This storage method eliminates the need for a high pressure gas tank, improving safety. The generated waste water is stored in an additional container. [28, p. 6]

2.5.2 DeepC

DeepC is a German AUV from ATLAS ELEKTRONIK GmbH that used a PEMFC consisting of two stacks with 60 cells each to generate its power. The DeepC submarine is the first AUV to use this source of energy, which enables missions up to 60 hours in length at depths of 4000 m. The FC is fully integrated in the pressurized hull and also includes batteries as a buffer together with electronics for power conversion and distribution. The power is distributed by a redundant power bus system with current limiting couplers without fuses, that enable safe and efficient energy management.[29]

2.5.3 IDEF

IDEF is a French research project. Similar to previous examples, it also uses a closed cycle PEMFC which produces 1.5 kW. Something which was not observed on other vehicles is that the pressure vessel is filled with nitrogen to avoid an explosive mixture of reactants. The waste water is again collected in an internal container to keep the weight constant. The reactants are stored in three 50 L cylinders, two for hydrogen at 300 bar and one for oxygen at 250 bar, providing 36 kWh of electrical capacity. [30]

2.5.4 Solus-Family

Cellula Robotics is a Canadian company specializing on advanced AUV systems. They have the product line Solus, which consists out of four AUVs, two of which are powered by a FC [31].

The smaller one is the Solus-LR. It uses a commercially available closed-loop PEMFC. The reactants are stored in high pressure tanks, providing more than 250 kWh of energy. For start-up or short silent operations a 4 kWh Lithium-ion (Li-ion) battery is also present. Wastewater is also stored in an extra tank to keep buoyancy constant during operation. [32, p. 15]

A bigger version, the Solus-XR, is currently performing sea trials, and is also powered by a FC. But apart from the operation time of up to 45 days and a range of 5000 km no information is currently publicly available. [31]

3 Concept

With the state of the art defined, the following sections present a concept for integrating a FC-HPS into the LoLo, detailing each subsystem of the HPS. To support the development of each subsystem, a high-level system overview was established early in the project. This overview, illustrated in Figure 3.1, outlines the energy and information flows, helping to define requirements and interfaces between subsystems.

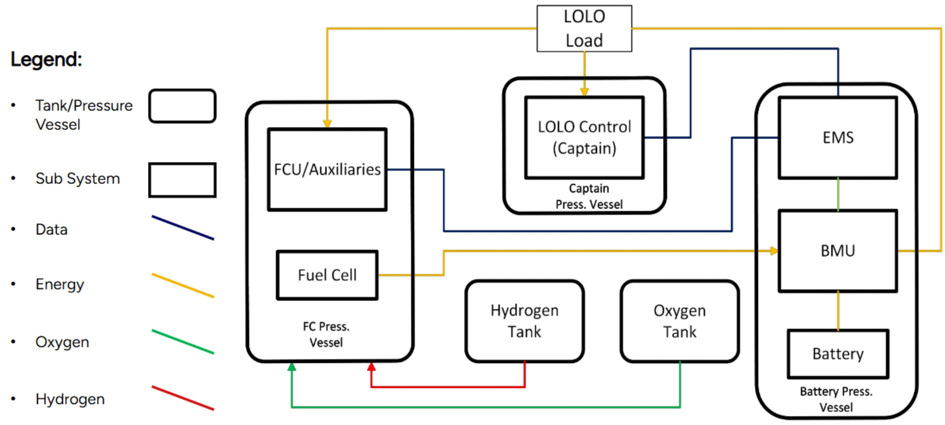

Figure 3.1: High-level system overview

3.1 Rechargeable Energy Storage

In chapter 2.2 three options for a short term energy storage are presented, these will be analyzed according to the requirements for the LoLo. For this energy storage, two constraints are provided by the stakeholders:

1. Shall fit inside an existing pressure vessel with a diameter of 170 mm and a length of 780 mm
2. Shall be able to provide power on its own to LoLo for at least one hour, which corresponds to an energy of more than 500 Wh
3. Shall be able to provide at least 2 kW of power.

In accordance with these constraints, the options are evaluated in the chapters below. It should be noted that combinations of different technologies are not considered, due to further increased complexity.

3.1.1 Flywheel

Although it is possible to create a FESS with a lot of capacity, usually the problem is the size constraint. Just the electric motor can exceed the size constraints of the pressure vessel. Furthermore, even if running in a vacuum to reduce drag, up to 250 W are necessary to keep the energy stored, and sudden torques would interfere with the control of the LoLo. This makes a FESS unsuitable for this project. [33, p. 3, 7]

3.1.2 Supercapacitor

Current supercapacitors have an energy density of approximately 8 Wh/L [34]. Assuming that the whole pressure vessel is used, this results in a capacity of approximately 140 Wh, far below the given requirements. Therefore it doesn't present a suitable option.

3.1.3 Battery

The existing pressure vessel previously contained another battery system, providing approximately 1.5 kWh of energy. So, it is definitely possible to meet the energy requirement. But it should be noted, that it is impossible to reuse this battery pack, since it has a higher voltage configuration and is therefore not adapted to the expected currents.

This means a redesign is necessary, but due to time constraints, it is decided to reuse as much of the existing hardware and software as possible. Therefore, a TinyBMS from enepaq is used. Since currents above 30 A are expected, the high current configuration with external contactors is used [35, p. 25]. For the communication between the BMS and the LoLo, a custom developed microcontroller called ISB is available. It already includes a barometer to read the pressure inside the containment and is compatible with leak sensors from BlueRobotics. Since the board is already used within the current setup of the LoLo, there are also libraries to communicate with all components available. An initial schematic, which has already been discussed with the stakeholders, on how all components can be connected, can be found in Appendix E.

Regarding the mechanical design of the battery pack, multiple design options are considered. To streamline the design and manufacturing process and accommodate the project's short timeline, the battery pack is separated from the rest of the electronics inside the pressure vessel. The cell chemistry, geometry, and size are analyzed by estimating the required battery pack length within the pressure vessel to meet the specified requirements. By evaluating different chemistry and geometries, prismatic and cylindrical cells, the design options are narrowed down to only the feasible ones. The two packaging strategies considered were stacked prismatic cells and cylindrical cells in a honeycomb structure.

Different lithium-ion chemistries offer trade-offs in energy density, cycle life, and safety. When evaluating the different options, the cell chemistry that emerges as the primary option is Lithium Iron Phosphate ($LiFePO_4$). This chemistry provides high safety compared to other Li-ion variants, $LiFePO_4$ cells are relatively resistant to thermal runaway [36, pp. 133]. The analysis of packaging strategies shows that cylindrical $LiFePO_4$ cells occupy only 25% of the pressure vessel's length, compared to 60% for prismatic cells, making the cylindrical option significantly more space-efficient. Other Li-ion chemistries are considered, but the reduction in pack size is limited to only 8 percentage points compared to $LiFePO_4$ for cylindrical cells and for prismatic cells, no reduction in size is achieved. Lead-Acid cells are also considered. However, their low energy density results in an unfeasibly large battery pack. When evaluating geometry and size, cylindrical cells significantly outperform prismatic ones in terms of space efficiency, regardless of chemistry, making them the preferred option in that sense. However, integrating cylindrical cells requires additional design work, as they require a more complex manufacturing process to establish reliable connections. In contrast, prismatic cells are typically supplied with screw-terminals, simplifying integration and making them the preferred choice for the project. It was considered feasible to fit the remaining electronics inside the pressure vessel, while the battery pack consisted of prismatic cells.

The mounting concept involves placing the system inside the pressure vessel using a technique currently employed by SMaRC, which utilizes Bosch rails. These rails are secured to the vessel's lid, providing structured support for the system's components. To reduce stress on the mounting points of the rails, additional supports against the vessel's inner wall are implemented.

3.2 Concept Fuel Cell system

Since this project is centered around the integration of a PEMFC in an AUV, a decision needs to be made whether to implement the conventional or the air-breathing approach, as well as how to handle increased humidity inside the FC pressure vessel due to the FC operation. These alternatives are now evaluated to together with the concepts for the hardware and software needed for the operation of the FC subsystem.

3.2.1 Conventional vs Air-breathing Fuel Cell

The FC used in the conventional models by both Calili-Cankir et al. [16] and Abdulrahman et al. [18] discussed in Section 2.1 uses pure oxygen as an oxidant. However, the stack from PowerCell that has been provided for our project is only certified for air as an oxidant [14, p. 12]. Since changing any dimensions of the FC internal components to increase the performance is not an option (see Section 2.1), two possible solutions remain. The first solution would be to supply the FC through a conventional approach by fetching air from an external tank. This is a simple solution, but it would substantially limit the amount of fuel that can be stored, since the stored air only contains 21% oxygen. A better solution would be to let the FC fetch the oxygen from the air inside the FC pressure vessel and continuously supply it with new oxygen from an external tank as the oxygen in the air is consumed (air-breathing approach). This would impose a larger safety risk, since pure oxygen is pumped into the FC pressure vessel, but would increase the amount of fuel that can be stored onboard. Thus, the air breathing approach is chosen as the concept of choice. In order to maximize performance, a compressor will be used for forced convection of the air into the FC, creating a semi-breathing FC system (see Section 3.2.4).

3.2.2 Humidity and water in the Fuel Cell Pressure Vessel

Integrating a semi-breathing FC into an enclosed pressure vessel introduces humidity challenges. When the FC produces power, it also generates heat and water, with each 20 L hydrogen tank yielding approximately 3 L of water (see Equation 3.1). Since tank volumes may vary to support longer missions, the design must account for condensation on internal components. A concept for this is described in Section 3.2.4. The pressure vessel itself is filled with atmospheric humidity which is typically 60% to 80% and therefore 10.38 $\frac{\mathrm{g}}{\mathrm{m}^3}$ to 13.84 $\frac{\mathrm{g}}{\mathrm{m}^3}$ of water in the air [37]. Taking the worst-case scenario of having a temperature of 4°C inside the pressure vessel will result in a maximum absolute humidity of 6.355 $\frac{\mathrm{g}}{\mathrm{m}^3}$. Considering the available air volume to expand in the pressure vessel of $0.07\,\mathrm{m}^3$, the humidity inside the vessel will reach 100%, and 3.12 kg of water condensation will end up on the components and the walls of the pressure vessel.

$$\begin{aligned} pV &= nRT \\ n_{\mathrm{H_2}} &= \frac{200 \times 10^5 \ \mathrm{Pa} \cdot 0.02 \ \mathrm{m}^3}{8.314 \ \frac{\mathrm{J}}{\mathrm{mol \cdot K}} \cdot 277.15 \ \mathrm{K}} = 173.59 \ \mathrm{mol} \\ m_{\mathrm{H_2O}} &= n_{\mathrm{H_2}} \cdot M_{\mathrm{H_2O}} = 173.59 \ \mathrm{mol} \cdot 0.018 \ \frac{\mathrm{kg}}{\mathrm{mol}} = 3.1246 \ \mathrm{kg} \end{aligned} \tag{3.1}$$

$$p_{sat} \approx 813,55 Pa (@4°C) \tag{3.2}$$

[38]

$$\rho_{H_2O,max} = \frac{p_{sat} \cdot M}{R \cdot T} = \frac{813,55Pa \cdot 0.018\frac{kg}{mol}}{8.314 \ \frac{\mathrm{J}}{\mathrm{mol \cdot K}} \cdot 277.15K} = 6.355 \cdot 10^{-3}\frac{kg}{m^3} \tag{3.3}$$

Having roughly 3 L of water in the vessel requires a concept to handle the water in the system to protect all the electrical components. The following concepts are analyzed closer:

- **Concept A - Water Separator with a bladder (Moisture Trap):** The water in the air is separated to keep the amount of water in the pressure vessel close to the saturation vapor pressure and therefore reduce the amount of condensation in the pressure vessel. The water is collected in a targeted manner and can be removed when the mission is finalized.
- **Concept B - Pump water out of the pressure vessel:** Collect the water with a water separator and pump it out of the pressure vessel via a valve opening.

Comparing both concepts with each other, the safety risk of concept B, that a malfunctioning valve or pump to get the water out of the pressure vessel against the overpressure outside outweighs the limitation of the design flexibility in the tank volume. Therefore, the concept A is implemented in the integration phase.

3.2.3 FC Software

As part of the system software development, personnel at Linköpings Universitet (LiU) has already designed and delivered a fully functional FCU Printed Circuit Board equipped with an integrated microcontroller (a STM32) and a base layer of software. The provided FCU runs a Real-Time Operating System (RTOS) with predefined threads and essential capabilities such as Controller Area Network (CAN) communication, Analog-to-Digital Converter (ADC) input handling, and general Input/Output (I/O) control.

The base software also includes a Simulink-compatible environment with integration into the MATLAB toolchain, enabling control algorithms to be designed, simulated, and tested directly within Simulink. Once validated, these models can be automatically converted into embedded

C code, compiled, and flashed onto the FCU.

Regarding the communication as described in Section 3.2.3 the FCU communicates internally via a CAN-Bus or I/O. Although this functionality is already available, additional CAN or I/O communication functionalities may still be required and can be added.

For communication with other subsystems and the EMS, the FCU will use RS-422 as the communication interface. This interface is to be implemented across all three subsystems and requires the same protocol and handling on both sides. For the implementation concept, see Section 3.3.2.

3.2.4 FC Hardware

This section describes the main hardware components required for integrating the FC system into the pressure vessel and outlines the rationale behind key design choices. The components and their interaction and loops are shown in Appendix F.

Fuel Cell The central component of the system is the FC itself. Currently, as stated in section 3.2.1 , SMaRC has acquired a PEMFC, which operates with ambient air rather than pure oxygen. This FC is capable of delivering a power output of up to 3 kW. For detailed specifications and further information, see the manual [14].

Sensors and Instrumentation Pressure sensors are essential for monitoring the hydrogen and air supply lines, ensuring that regulators and valves operate correctly and safely. These sensors allow the system to detect fault conditions such as overpressure or leaks, which is critical for both performance and safety. Temperature sensors are also strategically placed at key locations, including the FC stack, the coolant loop, and the ambient environment, to track thermal behavior and prevent overheating. In addition, a mass flow sensor installed within one of the compressors is being considered to monitor the flow rate, providing further insight into system efficiency and performance. To enhance diagnostic capabilities, a more comprehensive sensor unit known as the Cell Voltage Monitor (CVM) has been integrated into the system. The CVM continuously monitors the voltage of individual cells within the FC stack, allowing early detection of degradation or faults and supporting effective system maintenance and fault management.

Actuators Actuators play a crucial role in enabling movement and control within the system. Currently, the concept involves using a single compressor on the hydrogen side to recirculate hydrogen, maximizing fuel utilization and thereby improving overall efficiency. On the air side, the compressor primarily serves to regulate airflow, enhancing FC efficiency by pushing out excess water from the stack, preventing flooding and starvation, and supplying fresh oxygen as fuel. Additionally, a pump is used in the cooling circuit to circulate coolant through the FC stack. Depending on the implementation, this pump can either maintain circulation of a temperature-controlled liquid or actively cool the stack by leveraging the heat dissipation properties of the pressure vessel itself.

Valves and Flow Control Valves are used to regulate hydrogen and air flow. Normally Closed (NC) valves are selected for safety reasons, in the event of a power loss or system failure, the default state will isolate fuel sources, minimizing risk. Valves are placed before and after pressure regulators, and in the purge or exhaust lines, often in conjunction with overpressure relief valves to protect the vessel and FC-stack.

Piping and layout To support safe and efficient FC operation, the piping system must handle a significant pressure differential. This differential can be as high as 200 bar in the storage tanks compared to near-atmospheric pressure (1 bar) at the stack. Additionally, the system must ensure resistance to hydrogen leakage and high humidity. The current design incorporates a single hydrogen loop, a separate oxygen inlet, and a dual-loop cooling system controlled by a three-way valve. A shorter internal loop near the fuel cell manages warm-up and temperature stabilization, while a larger loop runs along the interior of the pressure vessel to maximize heat transfer. In this configuration, the vessel walls and surrounding water function as an active heat exchanger. Compact routing of all piping is critical to conserving space, minimizing dead volume, and managing thermal gradients. For a visual representation, refer to Appendix F.

Because this project involves the use of highly sensitive chemicals such as hydrogen, all high pressure piping up to the pressure relief valve will be designed and installed by an external company (Teramek). This company is responsible for ensuring safety and compliance with pressure regulations. Depending on final system design, the pressure relief valve may be located either inside or outside the pressure vessel.

Bladder and Dehumidifier As discussed in Section 3.2.2, managing water inside the pressure vessel is a critical challenge, and the current concept involves using a bladder system. This bladder is envisioned to be made from a flexible, elastically deformable material that can adjust its shape to the limited available space within the pressure vessel. The dehumidifier will collect the water produced by the FC stack, while the bladder will store this water until it can be flushed, purged, or otherwise removed from the system.

FCU and Electronics Space allocation for the FCU, currently based on an STM32 platform, and its associated electronics must account for thermal insulation, vibration damping, and protection against humidity. Depending on the expected thermal load and electromagnetic shielding requirements, the components may be placed in a dedicated enclosure within the pressure vessel. Alternatively, they may be housed in insulated compartments that utilize natural convection and heat dissipation through the vessel walls. In both cases, the design will be integrated into the aluminum Bosch rail frame, as described in the pressure vessel paragraph in Section 3.2.4.

FC Pressure Vessel Regarding the pressure vessel, system components will be housed in a sealed, pressurized container inside the LoLo, which operates in seawater at approximately 4°C, as shown in Appendix G. This harsh marine environment imposes strict spatial, thermal, and material constraints on the system. To address these challenges, a modular, drawer-like structure, based on aluminum Bosch rail profiles with dedicated compartments, has been considered, as described in Section 3.1.3. While similar rail systems have previously been used by SMaRC, the current design must be refined and adapted to support the specific requirements of the FC integration.

3.3 Concept for EMS

In this section, the chosen concept for the EMS is discussed together with the associated process and challenges in arriving to it.

3.3.1 EMS topology and Hardware

Before instigating a new design, the team analysed the existing proposals and solutions.

Initial Concept The first decision necessary to complete the hardware design was the system topology. This includes the physical placement of the EMS, as well as the communication and power connections required. The initial concept for the EMS developed by SMaRC and its partners revolved around isolating the FC components from the already existing battery system. This means that the EMS is physically located in the FC pressure vessel and only requires communication with the FCU and LoLo Captain. This design allows the FC to act as a completely standalone system, whilst retaining the use of at least one of the previous battery units. The battery unit continues to operate on its own, only sending data to the Captain. Based on this, a PCB was developed for the EMS, using an STM32 microcontroller, including 2 RS-422 Rx-Tx circuits, 3 analog inputs with instrumentation amplifiers, one SWD for debugging and capacity for 24V power input as seen in Appendix H.

Current Concept The original concept is complete and has made considerable progress in terms of implementation, but the team aims to alter some of the design choices. A primary concern is the placement of the EMS in the FC Pressure vessel. This is considered unideal, as the environment in this pressure vessel may be saturated with moisture. Additionally, any loss of this pressure vessel, or system failure of the FC could potentially damage the EMS. This entails that the Captain realise the loss of the FC and EMS, and performs some recovery on its own. A further concern is the direct communication of the BMS with the Captain, creating an additional data stream and further complicating the integration of the new hybrid system, by requiring the Captain to maintain two RS422 connections. Given that a new battery system is to be designed it is decided that the BMS will communicate and receive commands via the EMS. This allows the EMS further control options, reduces the communication load of the Captain and matches the typical system architecture found in most hybrid vehicles. Therefore, by placing the EMS in the Battery Pressure Vessel, as seen in Figure 3.2, several advantages are realized.

Nevertheless, this choice comes with some drawbacks. Challenges are introduced in measuring the power consumption of FC auxiliaries, EMS becomes a potential single point of failure, and an additional unplanned simple serial or RS422 connections needs to be implemented. These challenges are addressable, and are resolved in the integration stage of the project.

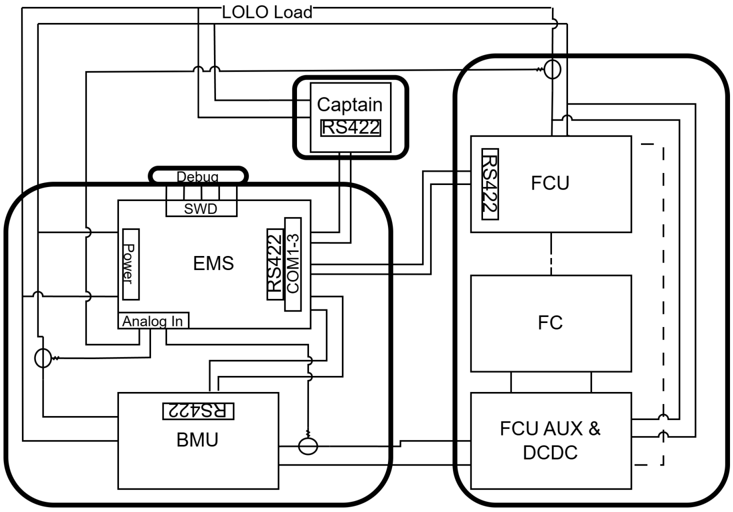

Figure 3.2: EMS focused system topology

3.3.2 Subsystem Signaling and Data Transfer

Given previous design choices at the system level (i.e. previous LoLo subsystem communication methods) and the EMS hardware level (e.g., EMS PCB design), the RS-422 standard is chosen as the physical layer for signaling and data transfer.

Physical Layer RS-422 is defined by a Telecommunication Industry Association (TIA) standard [39]. It is a simplex multidrop standard, meaning it supports one driver and up to ten receivers on a bus. RS-422 uses balanced voltage signaling, which is well suited for electrically noisy environments.

The standard is selected as the physical layer (OSI Layer 1) due to its robustness and suitability for harsh operating conditions. Differential signaling provides high immunity to electromagnetic interference and reduces the risk of signal degradation. RS-422 also supports data rates up to 10 Mbps (for short transmission distances such as those found in the LoLo), enabling high-speed communication [40, p. 3–9].

Data Link Layer RS-422 defines only the physical layer; it does not specify the communication protocol or message formatting. Therefore, a protocol is implemented at higher layers to manage framing, timing, and error detection. Given our hardware and topology (one full duplex for 2-way communication per device), an asynchronous protocol compatible with a full duplex setup is needed.

Given the common options for this layer Universal Asynchronous Receiver/Transmitter (UART) seems to be the most suitable choice. It is natively supported by most microcontrollers, including STM32, and integrates easily with RS-422 transceivers. UART provides asynchronous communication with built-in start/stop bits, optional parity, and does not require a shared clock, making it ideal for robust and lightweight full-duplex communication [41, p. 17-20].

Network to Application Layers Above the data link layer, several options can be implemented. For example Serial Line Internet Protocol (SLIP) which allows IP over serial or alternatively a custom binary protocol. These options are either limited to one OSI layer or are quite complex to implement, therefore the current thinking is to use Micro Air Vehicle Link (MAVLink). MAVLink, is a lightweight message-marshaling protocol designed for embedded systems using serial communication. It merges transport, session, and presentation responsibilities by embedding framing, sequencing, checksums, and routing within its structure [42, 42]. Its message schema is versioned, extensible, and tool-supported, reducing implementation errors. MAVLink has been adopted in multiple systems, and open standards have been designed based on it. For a system that relies on RS-422 and UART,MAVLink should provide an efficient and maintainable stack from the network to the application layer. It is also well documented and supported, meaning that working on it will present fewer problems than creating a custom, but simpler approach. The overview of the OSI layer stack can be seen in Appendix I.

3.3.3 EMS Controller

In the LoLo project, some work had already been undertaken to develop an EMS. Specifically, two different approaches were modeled using Simulink and Matlab. However, after the review of the State-of-the-art (SOTA), it is decided to test both the already implemented principles and design simpler potential options.

Developed Model Predictive Control (MPC) Previous work has been done on Model Predictive Control (MPC) for the LoLo as a masters thesis. The MPC strategy aims to optimize the division of the power between the FC and the battery. As the name suggests, the controller uses predictive models of the FC power, hydrogen consumption and battery State Of Charge (SOC) to minimize hydrogen consumption, avoid excessive changes in the FC power and maintaining a reference SOC of the battery. The MPC also follows system constraints such as hydrogen usage or FC ramp rate to make sure that the system is safe and efficient. This enables the AUV to meet different power demands while maximizing system longevity and mission length [43]. The mathematical formulation of the MPC is found in Appendix J.

Developed Equivalent Consumption Minimization Strategy The ECMS strategy aims to split the power demands between the battery and FC in a way that minimizes the equivalent cost of the two sources by assigning a cost to each energy method. This is then formulated as an optimization problem that tries to balance the FC and battery usage based on the SOC of the battery. The model of the controller is provided by Assoc. Prof. L. Feng by email [44]. The mathematical formulation of the ECMS is found in Appendix K.

Proposed Power Follower State Machine Instead of relying completely on previous work on more complex strategies, a simple state machine power follower is theorized as shown in Figure 3.3. Its primary goal is to reduce wear on the fuel cell by minimizing on/off cycles while satisfying the following constraints:

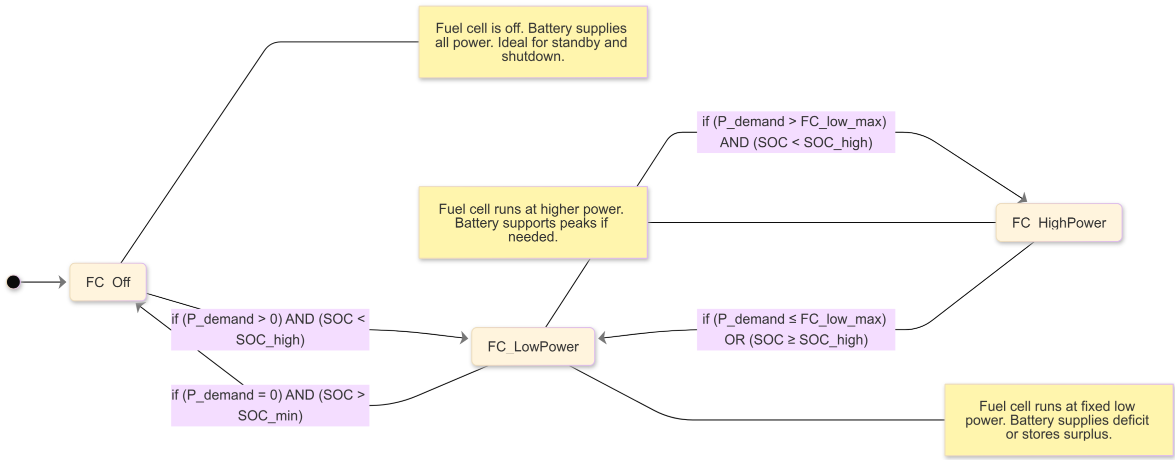

Figure 3.3: Proposed State Machine EMS approach diagram to be implemented in Matlab

$$P_{\text{fc}} + P_{\text{bat}} = P_{\text{req}}, SOC_{\text{min}} \leq SOC(t) \leq SOC_{\text{high}} \tag{3.4}$$

where $SOC(t)$ is the time-varying SOC, P_{fc} is controlled via discrete state transitions (Off, Low, High), and the battery compensates for any shortfall or absorbs excess energy. This approach hopes to leverage the FC's efficiency at stable operating points and the battery's responsiveness to transients.

Proposed Thermostat Control Another proposed control strategy is a simple thermostat controller. A simple rule-based controller aiming to keep the battery SOC within predetermined thresholds by turning the FC on or off depending on SOC. The basic equation for this control can be written as

$$P_{\text{fc}}(k) = \begin{cases} P_{\text{fc,nom}}, & \text{if } SOC(k) < SOC_{\text{low}} \\ 0, & \text{if } SOC(k) > SOC_{\text{high}} \\ P_{\text{fc}}(k-1), & \text{if } SOC_{\text{low}} < SOC(k) < SOC_{\text{high}} \end{cases} \tag{3.5}$$

where $P_{\text{fc,norm}}$ is the nominal power output of the FC, SOC_{low} and SOC_{high} is the lower and upper threshold for the battery SOC. This equation activates the FC if the battery SOC gets to low, deactivates the FC if the battery SOC gets to high and keep the FC at its previous stage if the battery SOC is within the thresholds.

With the system concept defined, the next chapter discusses how the project will progress during the fall semester, when the concept will be implemented.

4 Discussion and Future Work

For the fall semester, the team continues working within our dedicated sub-teams: battery, EMS, and FC. Regular meetings with stakeholders are scheduled to align, gather feedback, and address challenges as they arise. Additionally, the team members have booked a safety course for the 15th of September, enabling work to be conducted unsupervised in the SMaRC laboratory. To avoid delays, the plan includes a week to secure critical components before the end of the spring semester. This ensures that manufacturing and assembly proceed smoothly when the fall semester begins. At the beginning of the fall semester, the focus shifts to integration. The integration, combined with testing, is conducted in four stages as outlined in the project plan, gradually progressing from bench testing to full underwater validation. A comprehensive risk analysis, covering potential obstacles and mitigation strategies, is presented in Appendix L. With these measures in place, along with a structured project plan, the presented concept and continued support from our stakeholders, the team are confident in its ability to finalize the project on time.

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A Project Plan

The project plan outlines key milestones and phases for each subteam with synchronized deadlines. Timely completion of each phase is needed for collective progress.

						Re-exams																							
Milestone		Comment	CW 14	CW 15	CW 16	CW 17	CW 18	CW 19	CW 20	CW 21	CW 22		CW 35	CW 36	CW 37	CW 38	CW 39	CW 40	CW 41	CW 42	CW 43	CW 44	CW 45	CW 46	CW 47	CW 48	CW 49	CW 50	CW 51
	Initial Research		##	##																									
	Initial Concepts				##	##																							
	Write SOTA & Concept in Report					##	##	##	##																				
	Design Review Presentation						##																						
	Spring Term Presentation						##		########																				
	Spring Term Report + Individual Reflections				##	##	##			########																			
	Rehearsals							##																					
	Mid term checkpoint																		########										
	Design Review P2																						########						
	Spring Report																												
	Grand Finale HK 2025																											########	
	Final Indicidual Reflection meetings																												########
	System																												
Concept	Interconnection definition	Define system topology (Part of SOTA): - Power interconnections - Control signal topology - Physical topology																											
	State machine concept	Define concept controller behaviour																											

	Signal requirement definition	Define signal requirements: - Type, QoS, frequency etc
	List of components	Define Controller HW, connectors etc
	Concept placement	How to place FC & Battery within LoLo
	Initial Intreface software	Basic SW for recieving necessary signals
Integration	Integrate HW into LoLo	Place FC & Battery within LoLo
	Software integration	- Policy for charging/Discharging - Communication between Captain/FC/BMS Debuging & Optimizing
Testing	Communication/Control	Test Comms/Ctrl: -FCM -BMS - Relevent Sensors
	Full control of system	Dry system test
	Full control of system	Wet system test
Fuel-Cell		

Concept	Simulation and familarization with Technology	- fuel cell stack with hydrogen and air and coolant circuit - electrical circuit - includes SOTA and understanding fuel cells																											
	Control Design Simulation	- How to control Hydrogen, air flow and coolant circuit as well as electrical power																											
	List of components	- identify needed components and decide on specific components																											
	HW/EE Design	- how to fit in the pressure vessels (lolo)																											
Integration	Integrate Fuel Cell HW on a test stand	- drive fuel cell onn a test stand																											
	Integrate Fuel Cell into the pressure Vessel	- after successful test stand -> intgrate into pressure vessel																											
	Integrate into LoLo																												
Testing	Testing on test stand																												
	Testing in pressure vessel																												
	Testing within LoLo																												
	Battery																												
	initial research																												

	initial concepts																												
Concept	Documenting SOTA and Concepts																												
	Design Review Presentation																												
	Order parts																												
	Integrate battery HW on a test stand	- drive battery on a test stand																											
Integration	Integrate battary into the pressure Vessel	- after successful test stand -> intgrate into pressure vessel																											
	Integrate into LoLo																												
	Testing on test stand																												
Testing	Testing in pressure vessel																												
	Testing within LoLo																												

B Requirements

This project is confined to the exploration and evaluation of energy sources limited to fuel cells and a rechargeable energy storage, specifically, only PEMFC are considered; other types of fuel cells and energy sources are excluded from this study.

The research is conducted within the facilities available at KTH and the SMaRC. These facilities provide the necessary infrastructure for developing and testing maritime robotics, including design, software development, electronics, and mechanics .

This study is designed as a proof-of-concept, focusing on demonstrating the feasibility of integrating PEMFC and a rechargeable energy storage system within the specified context. It does not aim to develop or adhere to Swedish national standards or regulations for full-scale implementation.

The project operates within the timeframe of an 18-credit course, spanning from March to December/January (including a summer break from June till end of August - no access to KTH buildings in this time period). Consequently, all testing and results must be completed within this period to meet course requirements.

The project team consists of seven members selected by the teaching team of the Capstone course. This limitation ensures manageable collaboration and aligns with course guidelines.

Regarding resources, the project does not anticipate purchasing new materials or products unless approved or provided by KTH or SMaRC, according to the project budget of SMaRC

The following requirements document outlines the technical and functional specifications for each subteam for alignment with project objectives.

Stakeholder Requirements

Req_ID	Discipline (SYS / SW / EE / HW)	Requirement	Description	Remarks	Verification Result	Linked Requirements	Review Remarks
1	SYS	Integrate PowerCellution V-Stack 24 as a breathing Fuel Cell inside of a given pressure vessel					
2	SYS	Control of Hydrogen, Coolent fluent and Oxygen and Water output for the Fuel Cell					
3	SYS	Control the Fuel Cell power output					
4	SYS	Batteries need to be able to charge					
5	SYS	Batteries need to be able to provide energy					
6	SYS	Safety Functions: Batteries need to be supervised (Temperature?, Voltage?)					
7	SYS	Safety Functions: Supervision of key measurement outputs to ensure safe usage of the Fuel Cell					
8	SYS	Control Energy from Fuel Cell and Batteries					
9	SYS	Fuel Cell needs to be able to charge the Batteries					
10	SYS	Dimensions: Ideally fit everything in the given pressure vessels					
11	SYS	Control the breathing Fuel Cell environment (water, oxygen, humidity...)					
12	SYS	Power peak output of 2kW for 3 min					
13	SYS	Define a needed nominal power for the Fuel Cell					
14	SYS	Implementation of Communication protocoll					
15	SYS	The system does not need to be optimized for energy efficiency					
16		The start-up procedure does not need to be fully automated					
17		There are no strict requirements regarding system life expectancy					
18		Consider flexibility in the design (increase range for the FC; Switch to old battery system)					

System and Discipline Requirements Requirements

Req_ID	Discipline (SYS / SW / EE / HW)	Requirement	Description	Remarks	Verification Result	Linked Requirements	Review Remarks
1	SW	Check Fuel Cell - cell voltage continously every 45ms					
2	SW	Control measure if a single cell is 0,5 sec under 0,3V					
3	EE/HW	Manually measure the battery voltage	It shall be possible to manually measure the battery voltage without opening the pressure vessel				
4	EE	50 amps per cabel	The load on each power supply cabel sall not exceed 50 A				
5	EE	Electrical system shall be free-floating	Electrical system shall be free-floating (i.e., not referenced to chassis ground unless explicitly required)				
6	SYS	The system shall include leak detection functionality. water/pressure	Applies to battery				
7	SYS	The system shall provide control over when charging occurs					
9	EE/SYS	It shall be possible to charge the battery without requiring the rest of the HPS to be running					
10	EE	Appropriate fusing to the battery shall be implemented for electrical safety					
11	EE	The battery pack should have at least 500Wh of energy capacity					
12	EE	The battery pack should have aproximatly 24V nominal voltage					
13	EE	The battery pack should be able to provide 2kW of power for 3 minutes					
14	EE	The battery pack should be able to absorb regenerative spikes from the load.					
15	EE/HW	The battery system including EMS must fit inside given PV					

C Fuel Cell Losses

This section explain the irreversible losses limiting a FC's from being able to provide its ideal voltage. The current density regions where the cell voltage is affected by the different losses are illustrated in figure C.1.

The different losses affecting the FC performance are briefly described in the following:

- **Activation-related losses**: Losses from the activation energy of the electrochemical reaction at the electrodes (Depending on reaction at hand, electro-catalyst material and microstructure, reactant activities and weakly on the current density). If the electrochemical reactions the overpotential η_{act} >= 50 - 100 mV, it is possible to approximated the activation losses with the Tafel equation (see equation C.1)

$$\eta_{activation} = \frac{R\,T}{\alpha\,n\,F} \ln \frac{i}{i_0} \tag{C.1}$$

  where R is the universal gas constant, T is the temperature, α is the electron transfer coefficient, n is the the number of electrons exchanged, F is Faraday's constant, i is the current density, and i_0 is the exchanged current density.

- **Ohmic losses**: Flow resistance of the ions in the electrolyte and of the electrons through the electrode (Depend on material selection, stack geometry and temperature - proportional to current density). The ohmic resistance is normalized by the active cell area with the key figure Area Specific Resistance (ASR) in Ω/cm^2.

$$R = R_{electronic} + R_{ionic} + R_{contact} \tag{C.2}$$

- **Mass-transport-related losses** resp. **Concentration losses**: Finite mass transport limitation rates of the reactants (Depend on current density, reactant activity, electrode structure). These losses occur due to the absence of reactants at the electrodes at high current densities resp. high reaction rates [45, p. 3]. The regions in an FC's cell voltage vs current density curve affected by the different losses can be seen in figure C.1 down below.

[12, pp. 2-10]

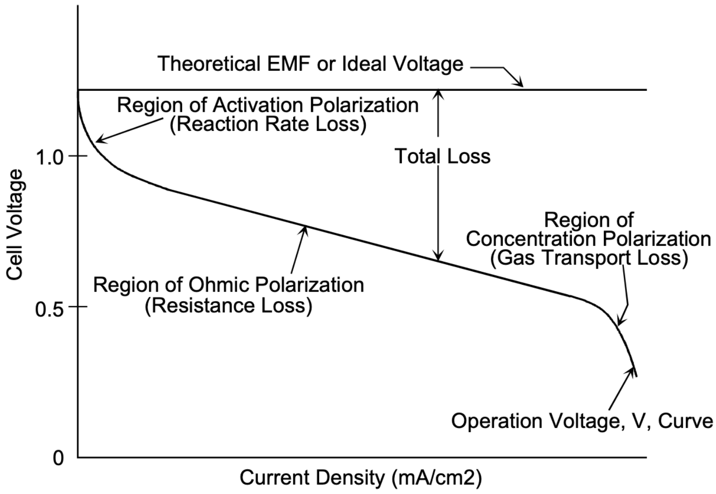


Figure C.1: Ideal and Actual FC Voltage/Current Characteristic [12, p. 2-11]

D EMS Control Strategy Mapping Diagram

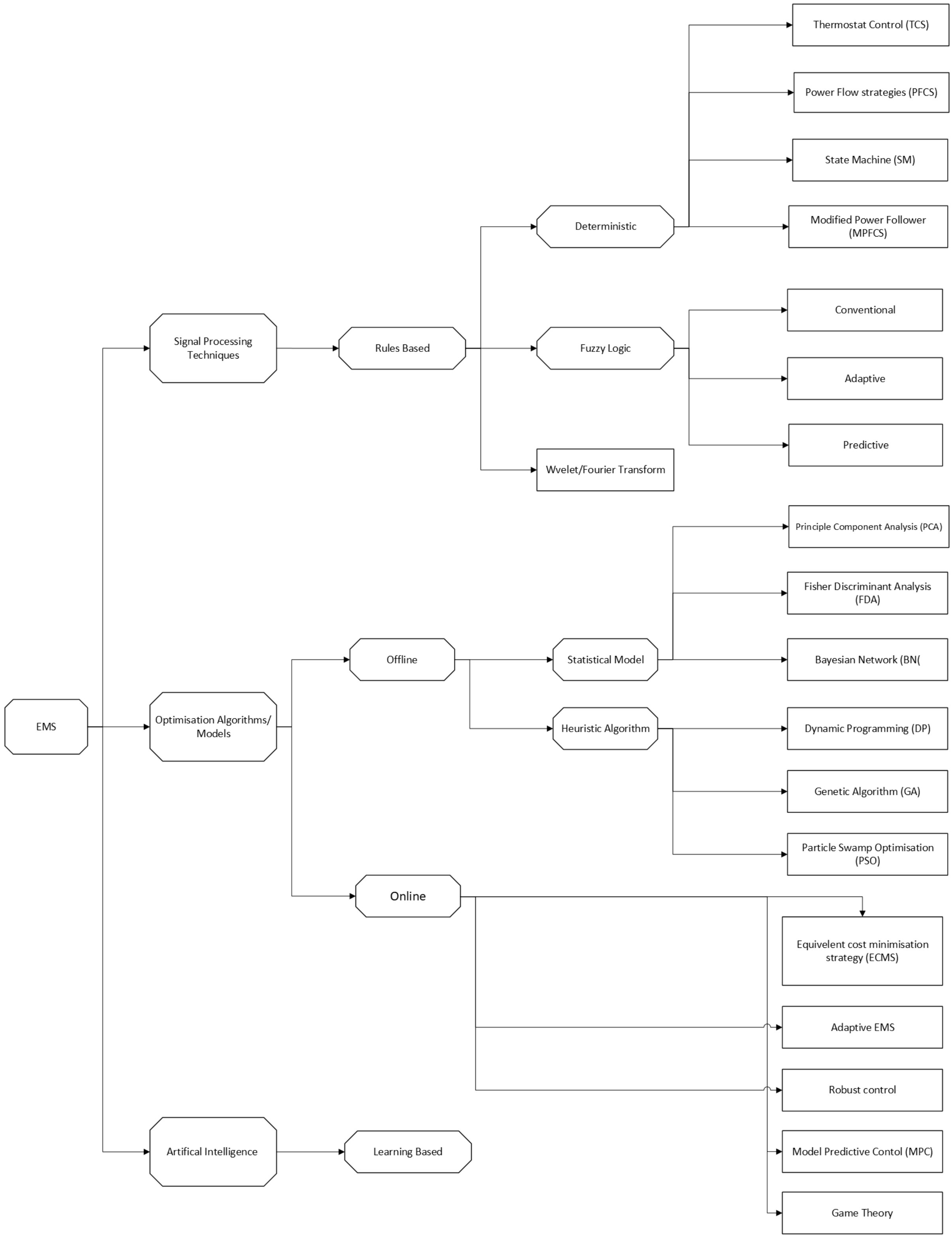
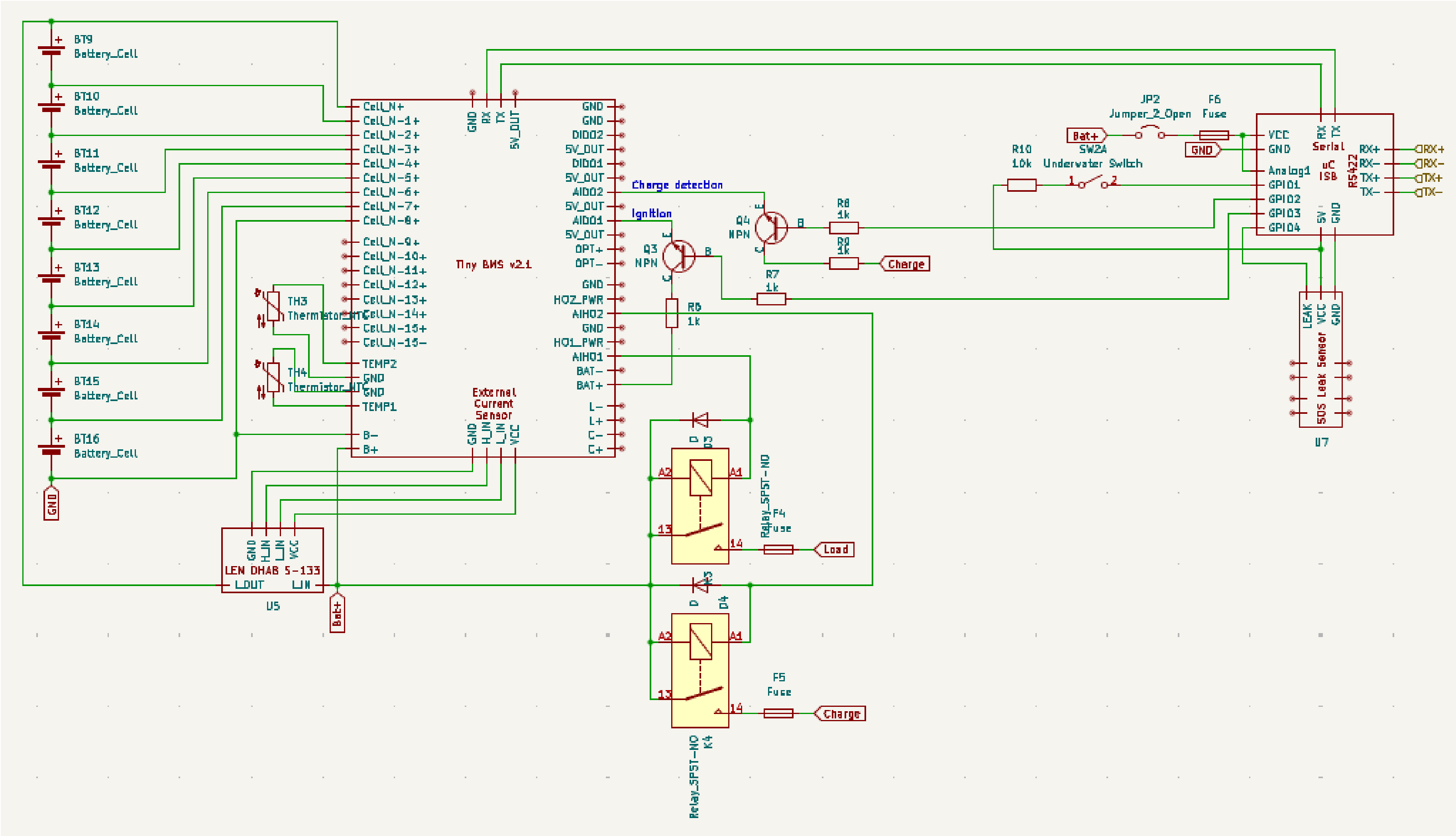
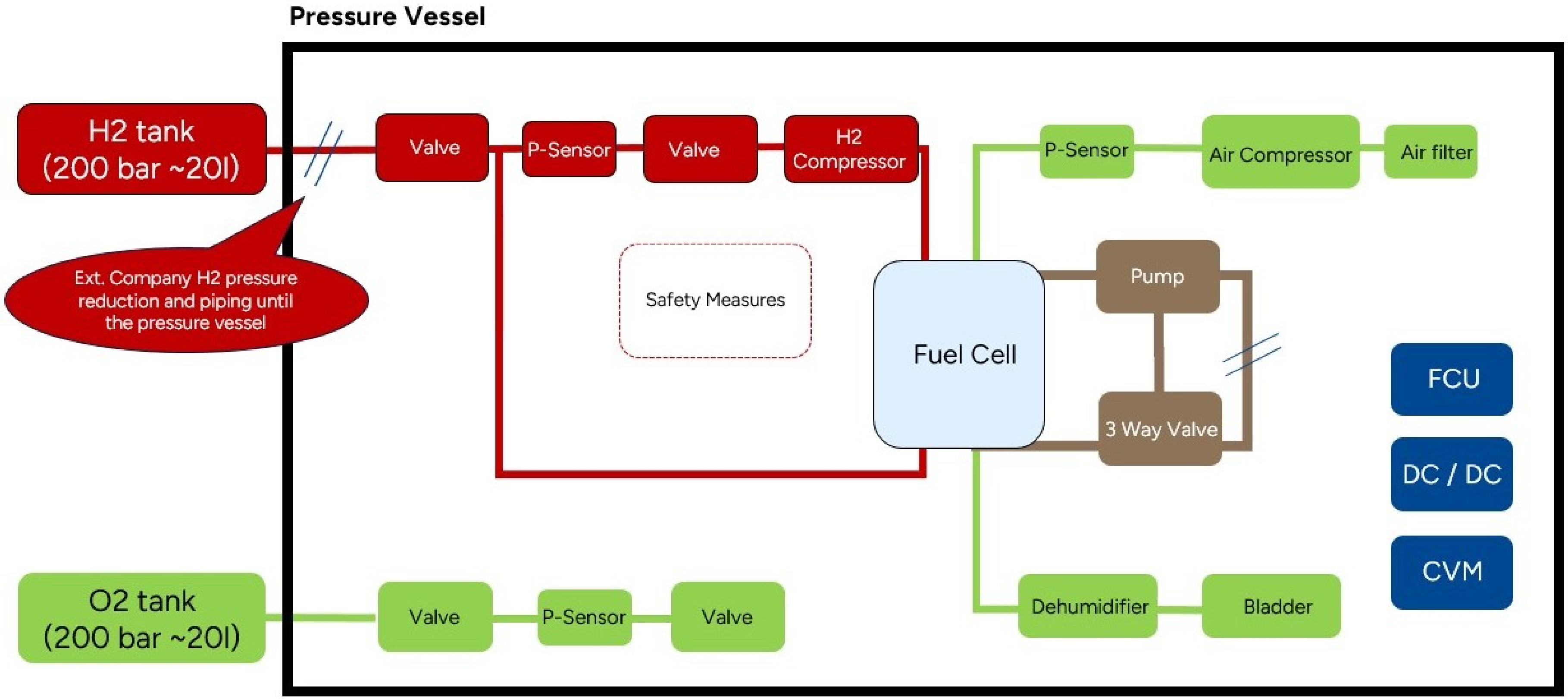


Figure D.1: EMS strategy categories and methods, adapted from [23, pp. 1382–1385], [25, pp. 192–195]

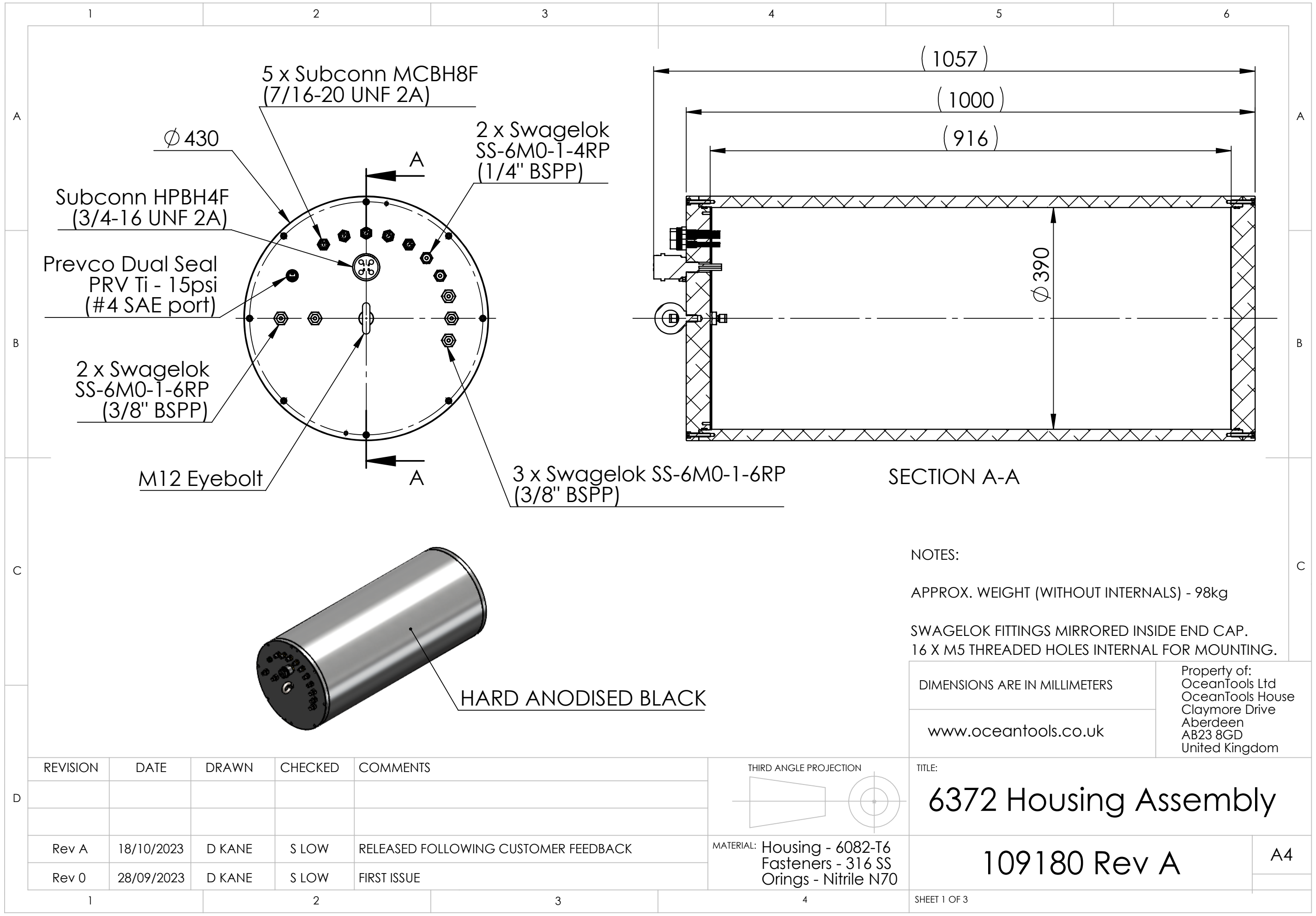
E Battery Schematic



F Fuel Cell Component Diagram



G Pressure Vessel Housing Assembly



H EMS STM32-based PCB Circuit Diagram

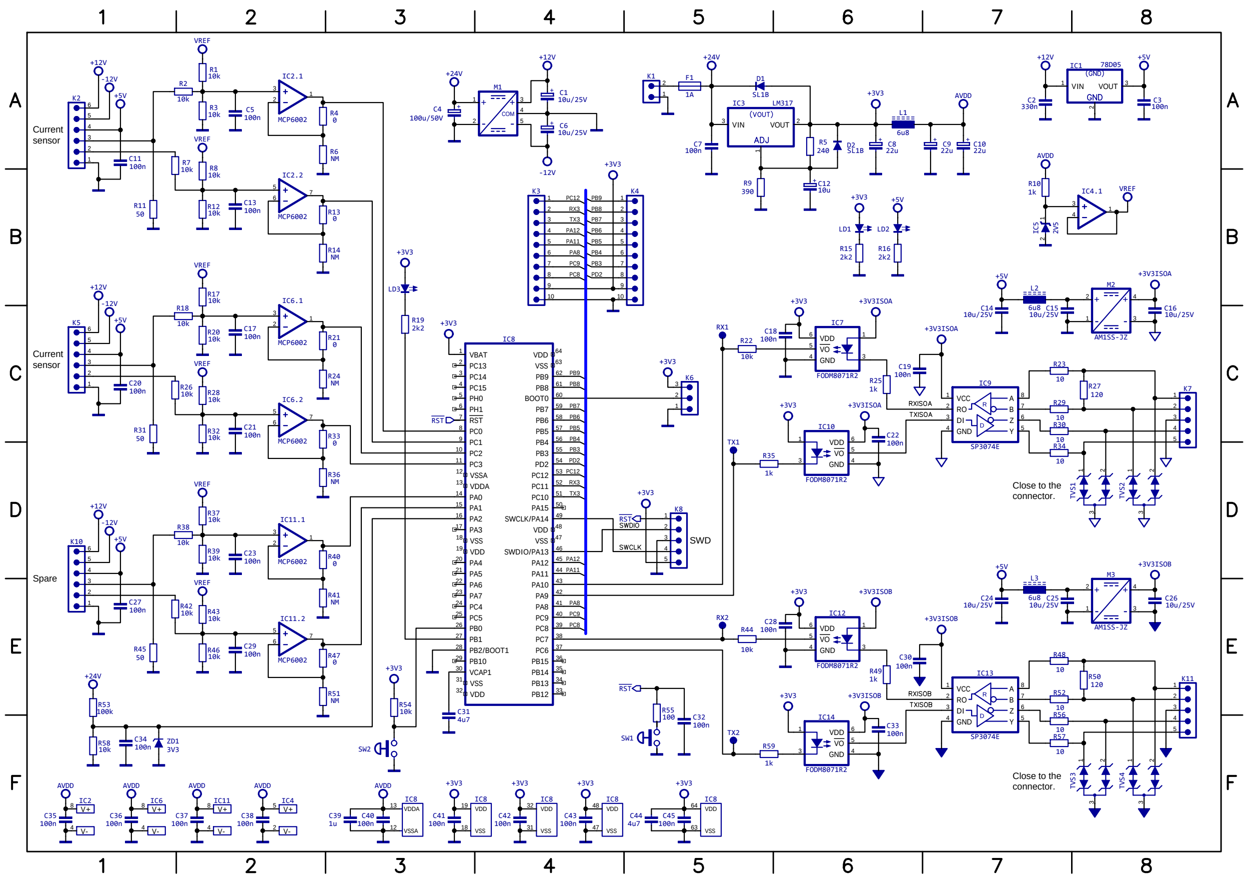


Figure H.1: EMS PCB designed by Mikael Hellgren, including an STM32-based microcontroller, RS422 connectors, analog inputs, 24V power input, and SWD interface.

I Proposed OSI Layer Architecture

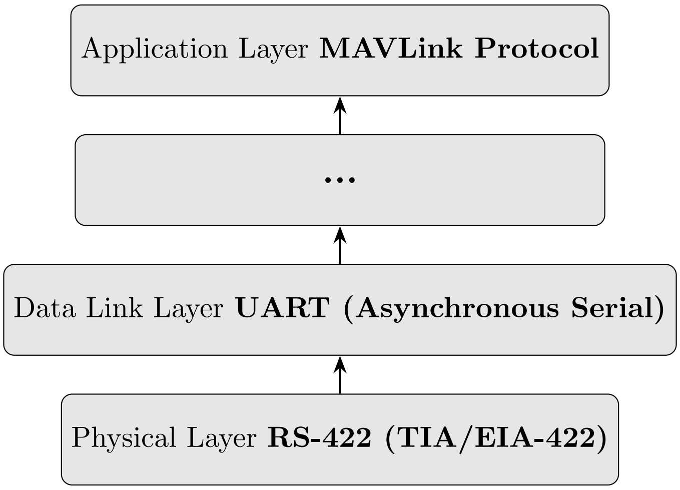


Figure I.1: OSI model layers for RS-422 full duplex communication system, showing UART as Data Link Layer and MAVLink handling all higher layers.

J MPC Mathematical Formulation

This appendix presents the detailed mathematical formulation underlying the predictive energy management system. The model includes several key components: the FC power model, which calculates net output by accounting for stack voltage, current, and compressor losses; the hydrogen consumption model, which tracks fuel usage over time; and the battery model, which describes the SOC dynamics and monitors battery current to ensure safe operation. These elements are integrated within a MPC framework, which optimizes an objective function that balances SOC regulation, fuel cell efficiency, and power smoothness. Finally, a set of operational constraints is applied to ensure the system remains within safe and efficient limits.

The FC power in this model is calculated as

$$P_{\mathrm{fc}}(k) = V_{\mathrm{cell}}(k) \cdot I_{\mathrm{cell}}(k) \cdot N_{\mathrm{fc}} - P_{\mathrm{comp}}(k) \tag{J.1}$$

where $P_{\mathrm{fc}}(k)$ is the net FC power at time k, $V_{\mathrm{cell}}(k)$ is the cell voltage, $I_{\mathrm{cell}}(k)$ the cell current and N_{fc} the number of cells in the FC stack. $P_{\mathrm{comp}}(k)$ is the power loss from the compressors in the system.

The hydrogen consumption model is used to track how much hydrogen is used over time to make sure the system doesn't run out of fuel. It is formulated in two stages, consumed hydrogen per time step and cumulative hydrogen consumption. The respective equations are

$$m(k) = \frac{I_{\mathrm{fc}}(k) \cdot M_{H_2}}{n_{H_2} \cdot F} \cdot \Delta k \tag{J.2}$$

where M_{H_2} is the molar mass of hydrogen $(2.016 g/mol)$, F the Faraday's constant $(96,485 C/mol)$ and n_{H_2} is the number of electrons involved per mole in the reaction. And

$$M(k+p) = \begin{cases} 0, & \text{if } k+p=0 \\ M(k+p-1) + m(k+p), & \text{if } k+p \geq 1 \end{cases} \tag{J.3}$$

where $M(k+p)$ is the total mass of hydrogen in grams that have been consumed at the future timestep $k+p$.

The SOC of the battery is represented in the model as

$$SOC(k+p) = SOC(k) - \frac{P_{\mathrm{b}}(k)}{V_{\mathrm{b}}(k) \cdot Q} \cdot \Delta k \tag{J.4}$$

where $V_{\mathrm{b}}(k)$ is the battery pack voltage at the current time step, Q is the total battery capacity and $P_{\mathrm{b}}(k)$ is the battery power at the current time step, where a positive value means discharging and a negative means charging of the battery.

The model also monitors the current $I_{\mathrm{b}}(k)$ in the battery at each time step in order not to exceed maximum or minimum battery power using the formula

$$I_{\mathrm{b}}(k) = \frac{P_{\mathrm{b}}(k)}{V_{\mathrm{b}}(k)} \cdot \Delta k \tag{J.5}$$

The objective of this MPC is to maximize the function

$$\begin{aligned} J(k) = \lambda_1 \sum_{p=1}^{N_p} \left(\frac{SOC(k+p|k) - SOC_{\mathrm{ref}}}{SOC_{\mathrm{max}} - SOC_{\mathrm{min}}} \right)^2 \\ + \sum_{p=0}^{N_u} \left[\lambda_2 \left(\frac{P_{\mathrm{fc}}(k+p|k)}{P_{\mathrm{fc,max}} - P_{\mathrm{fc,min}}} \right)^2 + \lambda_3 \left(\frac{\Delta P_{\mathrm{fc}}(k+p|k)}{\Delta P_{\mathrm{fc,max}}} \right)^2 \right] \end{aligned} \tag{J.6}$$

where Np is the predicted future number of steps and Nu is the predicted future number of steps where control is applied. λ_1 is the weighting factor for the SOC error, λ_2 is the weighting factor for the power of the fuel cell and λ_3 is the weighting factor for changes in the power of the fuel cell. The MPC model also applies some constrains to maximize the lifespan of the system and to respect the limits of the hardware. This constraints are

$$\begin{cases} 0.2 \leq SOC(k+p \mid k) \leq 0.8, & \text{State-of-Charge bounds} \\ -100 \text{ W} \leq \Delta P_{\mathrm{fc}}(k+p \mid k) \leq 100 \text{ W}, & \text{FC ramp rate limit} \\ 0 \leq M(k+p \mid k) \leq 650 \text{ g}, & \text{Hydrogen capacity limit} \\ 100 \text{ W} \leq P_{\mathrm{fc}}(k+p \mid k) \leq 2537 \text{ W}, & \text{FC power bounds} \\ -105 \text{ A} \leq I_{\mathrm{b}}(k+p \mid k) \leq 105 \text{ A}, & \text{Battery current bounds} \end{cases} \tag{J.7}$$

K ECMS Mathematical Formulation

This appendix presents the implementation of an ECMS, using a set of equations is defined to model the power flow and guide the optimization process. These equations quantify the balance of power between the battery and fuel cell, define the cost function to be minimized, and impose operational constraints on the system. The formulation begins with the battery power balance, followed by the equivalent cost function, its derivative for efficiency optimization, and the necessary constraints.

The battery power balance is formulated as

$$P_{\text{bat}} = \max(P_{\text{mot}}, P_{\text{fc,idle}}) - P_{\text{fc,req}} \tag{K.1}$$

where P_{bat} is the terminal power from the battery, P_{mot} is the power demand from the motor, $P_{\text{fc,idle}}$ is the idle FC power and $P_{\text{fc,req}}$ is the requested FC power. This equation describes the difference between the required motor power and the requested power from the FC. If the battery power is positive it indicates a discharge of the battery, and if it is negative it indicates charging.

The equivalent cost function is then formulated as

$$J = I_{\text{fc}} + \lambda_{\text{bat}} \cdot S_{\text{fc,last}} \cdot P_{\text{bat}} \tag{K.2}$$

where I_{fc} is the FC current, λ_{bat} is the weighing factor that adjusts the battery contribution to the cost function depending on the SOC. $S_{\text{fc,last}}$ is the FC current to power sensitivity at the previous step and can be written as $\frac{dI_{\text{fc}}}{dP_{\text{fc, last}}}$. This equation represents the costs of using battery power and FC current and adapts the energy usage based on the calculated costs.

The derivative of the equivalent cost function is also used to speed up the convergence and is formulated as

$$\frac{dJ}{dP_{\text{fc,req}}} = \frac{\partial I_{\text{fc}}}{\partial P_{\text{fc,req}}} - \lambda_{\text{bat}} \cdot S_{\text{fc,last}} \tag{K.3}$$

The goal of this method is to find the value of $P_{\text{fc,req}}$ such that the equivalent cost J is minimized. This can be written as

$$\min_{P_{\text{fc,req}}} \quad J \tag{K.4}$$

To ensure the operational safety and smooth operation of the system, the range of the power request from the FC is formulated as

$$P_{\text{fc,req}} \in [\max(P_{\text{fc,last}} - 100, P_{\text{fc,idle}}),\ \min(P_{\text{fc,last}} + 100, P_{\text{fc,max}})] \tag{K.5}$$

where $P_{\text{fc,max}}$ is the maximum safe power limit of the FC. The output of this gives us the optimal FC power and, by extension, also the corresponding battery power required to meet the total power demand.

This ECMS has been implemented in Matlab using the built in $fmincon$ solver. The solver is configured to use a Sequential Quadratic Programming Algorithm to ensure fast convergence.

L Risk Analysis

This is the risk analysis for the project, covering identified risks, their potential impact, and proposed mitigation strategies. The risk assessment template was provided by Oregon State University.

Risk Assessment Spreadsheet
Use to identify, assess and take action to address risk

Oregon State University

Department/Unit Name:	LoLo
Administrative Structure:	
Completed By:	
Date Completed:	
Date of Next Risk Assessment:	

Click to update Heat Map

What is the objective, goal or business matter you are seeking to achieve? Integrate a Fuel Cell Hybrid System into the LoLo submarine

What is the risk?*	Identify the Risk Category and briefly describe the identified risk	How is risk currently managed?	Comments/Concerns	Impact	Likelihood	Risk Calculation			Who should be involved in the discussion and decision making?	Do you need to do anything else, more or less, to reduce or control the risk?	Which Management Strategy (mitigate, transfer, avoid, accept) did you identify to control the risk?	Responsible Person/Job Title	Target Completion Date
						Impact	Likelihood	Risk Score					
H2 Valve Failure		Not	Could lead to output power drop -> Cannot open or leaking of hydrogen into the FC system -> Unintended opening	Significant	Medium	4	3	12	FC Team and Björn, Max (LiU)	Understand the likelihood of the valve control failing	TBD		
H2 Pressure Sensor Fail	Fuel Cell	Not	Control needs to bring the System into a safe state -> Losing most likely dynamic control abilities	Moderate	Medium	3	3	9	FC Team and Björn, Max (LiU)				
FC Control Failure	Fuel Cell	Not	- Starvation - Flooding (Water) - Overtemperature - Increased Degradation => Destruction	Significant	Low-Medium	4	2	8	FC Team and Björn, Max (LiU)				
CVM Failure	Fuel Cell	Not	Need to shut down the system (cut power etc.)	Significant	Low	4	1	4					
Cooling Failure	Fuel Cell	Not	- Valve, Pump, Temp sensor failure => No control over temperature of the FC System => Fail Safe State (Small stack, low power and in an cold environment) - Startup issues - Cold start possible	Moderate	Low-Medium	3	2	6					
Flooding Pressure Vessel - FC	System	Not	- Electronic components damaged - System shutdown most likely	Catastrophic	Low-Medium	5	2	10					
O2 System	Fuel Cell	Not	- Failure: flow rate (Pressure Sensor, Valve) - Starvation due to not providing sufficient O2	Significant	Low-Medium	4	2	8					
Leaking Piping	Fuel Cell	Not	- Lose efficiency until starvation - Damage of components/system to failure - Budget impact - Damage of environment (e.g. cooling system) => Properly working system not ensured	Significant	Low-Medium	4	2	8					
H2 Handling	Team and Lab	Not	- Physical and infrastructure risk	Catastrophic	Low	5	1	5			Mtigated - Safety course - Contained Lab environment with sufficient safety infrastructure		
Flooding Pressure Vessel - Battery	System	Not	- Electronic components damaged - System shutdown most likely - Need to surface	Catastrophic	Low-Medium	5	2	10	Battery Team/EMS Team/Niklas	- Leak detection in real time - Surfacing if leak detected - Pressure messurments performed to ensure a good seal.	Mitigate and reduce impact		
Battery Fire	Battery	Not	- Loss of power - Damaging of components => When pressure vessel brakes, seawater will control/choke the fire	Catastrophic	Low-Medium	5	2	10	Battery Team/Niklas	- Fuse - BMS disconnects the battery during overcharge, overcurrent, or overtemperature conditions	Mitigate		
Battery Handling	Team and Lab	Not	- Physical and infrastructure risk	Catastrophic	Low	5	1	5			Mitigated - Contained Lab environment with sufficient safety infrastructure		
Battery Failure	Battery	Not	- Loss of Battery power (running out of charge/Circuit broken etc.) => Loss of Power in the whole System => LoLo surfacing due to design	Catastrophic	Low-Medium	5	2	10	Battery Team/EMS Team/Niklas	- SOC/SOH tracking - Safe shutdown procedure	Mitigate and reduce impact		
Short Circuits	Battery	Not	- Fire - Damaging of components	Catastrophic	Low	5	1	5	Battery Team/Niklas	- Perform a system check before startup - Initial start up with external power supply - Free floating system - Fuse	Mitigate and reduce impact	Commissioner	
EMS Failure	System	Not	- Loss of efficiency - False shutdown of subsystem - Loss of communication (subsystem / Captain) => Power failure (LoLo surfacing)	Catastrophic	High	5	5	25	EMS Team/Niklas				