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College of Engineering and Technology

School of Mechanical, Materials, and Manufacturing Engineering

Department of Mechatronic Engineering

Development of a 6 DOF Stewart platform Force Balance for a Low Speed Wind Tunnel

Final year project (FYP 18-14)

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Declaration

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Abstract

Obtaining and simulating the aerodynamic performance of items in a windtunnel is a signifacent and important part of development of vehicles, aircraft and other machines that require aerodynamic performance evaluation. As a result due to complex maneuvers that may be required to be simulated there is a need for a dynamic positioning in the wind tunnel especially for aircraft. As a result the proposal for a stewart platform to replicate complex maneuvers during wind tunnel tests as well as position the model to obtain the required data.

This project will look into the modelling, simulation and development of a stewart plaform based force balance for a small low speed wind tunnel. The project will utlize matlab/ simulink for modelling and simulation as well as autodesk inventor for the mechanical design. A robust control system will also be developed for the stewart platform. Finnally the project will be developed and tested in a wind tunnel to evaluate the performance of the platform. The force balance and platform should be able position the test item and measure forces as well as calculate the aerodynamic coeficients using a beespoke computer program

Keywords: .

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1 Introduction

1.1 Background

Research on Fuel cells started in 1801 when British Chemist Humphry Davy was setting up experiments to assist him in separating several materials using voltaic piles. The experiments set the background for the development of fuel cells which Christian Friedrich Schönbein worked on in 1838. Sir William Grove was the first scientist to prove that reaction between hydrogen and oxygen produced electricity in 1939. He carried out experiments on water electrolysers and fuel cells using his background on electrolysis to come up with a reverse process to generate electricity. He succeeded in building a device that combined water and hydrogen to generate electricity. The new device was originally called a gas battery, but later was renamed the fuel cell.

The first operational fuel cell was developed by Charles Langer and Ludwig Mond. The duo developed a functional fuel cell, obtaining fuel capacity of 0.73V at 20A/m2. Francis Bacon advanced the Mond and Langer fuel cell in 1958, which was later used in the Apollo mission in 1969. Since then, the space agencies have been using fuel cells to power the space crafts and provide water for the astronauts.

With the current global challenge in the energy sector, there is an increasing need for power generation with minimal pollution and environmental degradation. As a way of mitigating environmental pollution and providing energy shortage routes, Fuel Cell technologies have been considered as elements of alternative energy systems. These technologies capitalize on high efficiencies (between 50–65 percent, Supramaniam, et al., 1999 [5]) and low emissions.

Fuel cells are increasingly becoming a promising alternative to internal combustion engines (ICEs) and thus are considered for transportation (automotive, marine and aerospace)

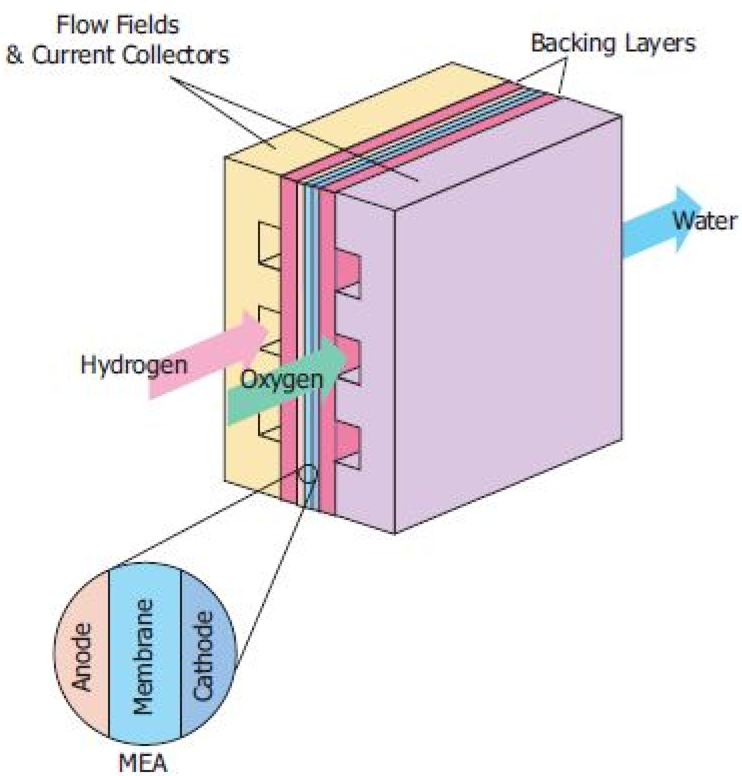

Figure 1.1: Fuel Cell Structure [1]

applications. They are also being considered for distributed power generation for residential homes and industries. Another promising use of FC stacks is for electricity storage in conjunction with electrolyzers and hydrogen accumulators.[2]

Power generation from Fuel Cells (FC) necessitates the integration of chemical, fluid, mechanical, thermal, electrical, and electronic subsystems. This integration presents many challenges and opportunities in the mechatronics engineering field. A fuel cell system is made up of a water and heat management system, an air system, a humidifier system and a hydrogen in-out let system. For optimum operation of the Fuel cell, some factors must be controlled - these are: the hydrogen flow, air supply, water cooling temperature, membrane temperature and humidity. Control strategies are therefore imminent so that the FC operates within some established limits such as electric power, pressure of the fuel gas and amount of air for the anode chemical reaction.

There are several types of fuel cells, each using a different chemistry. The common types of fuel cells are:

- Polymer electrolyte fuel cells
- Direct methanol fuel cells
- Alkaline fuel cells
- Phosphoric acid fuel cells
- Solid oxide fuel cells
- Reversible fuel cells
- Molten carbonate fuel cells

Polymer electrolyte fuel cells and alkaline fuel cells were the commonly used fuel cells for space missions. Development of fuel cells for commercial activities started in 2007, with an interest to develop fuel cells for automobile applications. The Polymer Electrolyte membrane (PEM) fuel cell is commonly used to power vehicles. Currently, the Polymer Electrolyte Membrane (PEM) Fuel Cells (also known as Proton Exchange Membrane Fuel Cells) are considered by many to be in a relatively more developed stage for ground vehicle applications. PEM Fuel Cells have high power density, solid electrolyte, long cell and stack life, as well as low corrosion. They have greater efficiency when compared to heat engines and their use in modular electricity generation and propulsion of electric vehicles is promising [6]. This proposal will focus on the design and development of a control system for a Proton Exchange Membrane Fuel Cell (PEMFC).

1.2 Basic Operation Principle of a Hydrogen Fuel Cell

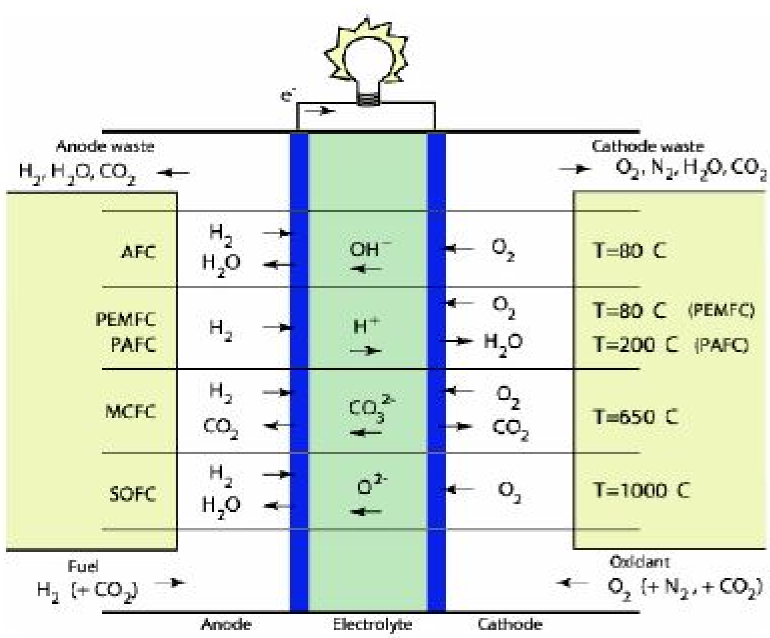

Figure 1.2: Fuel cell types and their respective operating temperatures [2]

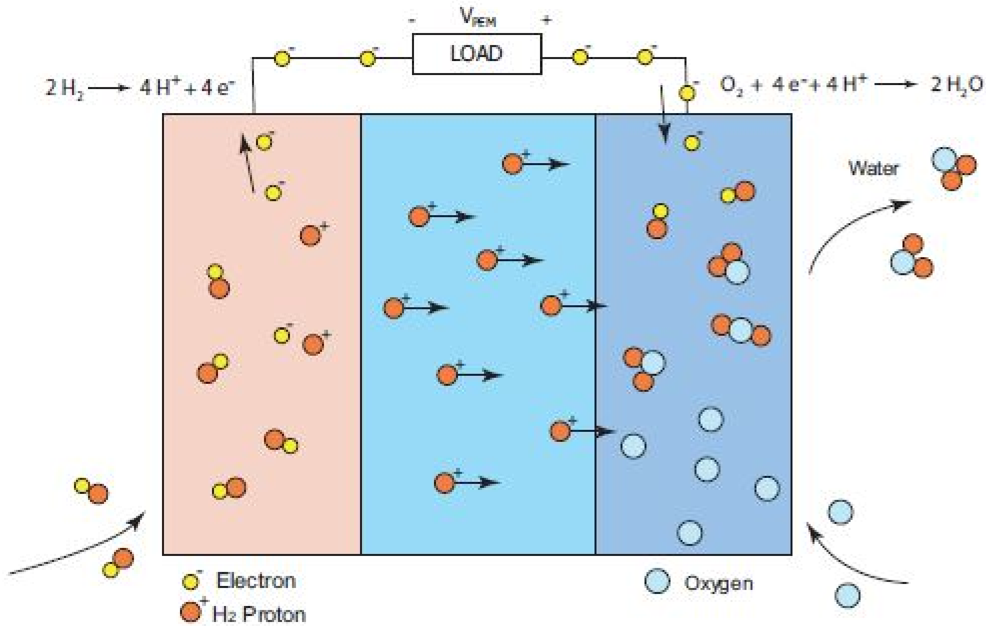

Figure 1.3: Fuel Cell Reactions [1]

Fuel cells convert chemical energy sources directly to electricity. A fuel cell consists of an electrolyte sandwiched between two electrodes. The electrolyte has a special property which allows protons to pass through while blocking electrons. Hydrogen gas passes over one electrode, i.e. an anode, and with the help of a catalyst, separates into electrons and hydrogen protons.

$$2H_2 \rightarrow 4H^+ + 4e^- \tag{1.1}$$

The protons flow to the other cathode through the electrolyte while the electrons flow through an external circuit, thus creating electricity. The hydrogen protons and electrons combine with oxygen flow through the cathode, and produce water.

$$O_2 + 4H_2 + 4e^- \rightarrow 2H_2O \tag{1.2}$$

The overall reaction of the fuel cell is given by:

$$2H_2 + O_2 \rightarrow 2H_2O \tag{1.3}$$

1.3 Problem statement

As a measure to curb pollution due to the industrialization and transportation sectors, world governments are turning to alternative sources of energy. These alternative sources of energy should drastically reduce the pollution rates by cutting down emissions. Fuel cell technology is one such example of alternative sources of energy. A fuel cell uses the chemical energy of hydrogen or other fuels to cleanly and efficiently produce electricity. Moreover, fuel cells can operate at higher efficiencies than combustion engines and can convert the chemical energy in the fuel directly to electrical energy with efficiencies capable of exceeding 60%. Fuel cells have lower or zero emissions compared to combustion engines.

The various departments of energy, however, have to work closely with national laboratories, universities, and industry partners to overcome critical technical barriers to fuel cell development. These barriers are cost, performance, and durability which are still key challenges in the fuel cell industry.

This design proposal seeks to provide a solution to improving the fuel cell's performance by improving the robustness and efficiency of the Fuel Cell stack system for real world conditions through precise control of reactant flow and pressure, stack temperature, and membrane humidity[2].

1.4 Objectives

1.4.1 Main Objectives

1. To develop a Hydrogen Fuel cell control system.

1.4.2 Specific Objectives

1. To design and additively manufacture a PEMFC prototype which can be adapted for domestic use and scaled for industrial applications.

2. To design and fabricate supporting control electronics for the Hydrogen Fuel Cell.

3. To achieve precise control of reactant flow and pressure, stack temperature, and membrane humidity.

4. To simulate and test alternative control strategies for the Hydrogen fuel cell.

1.5 Justification of the study

Additive manufacturing offers the ability to produce intricate products and parts with lower development costs, shorter lead times, less energy consumed during manufacturing as well as less material waste. This method can be used to manufacture delicate components such as the bipolar plates with elimination of the risks involved such as breakage of brittle graphene material during production.

Precise control of reactant flow and pressure, stack temperature, and membrane humidity will increase the fuel cell's robustness as well as efficiency [2][7][8].

The goal of this research is to develop physic-based dynamic models of fuel cell systems and fuel processor systems and then apply multivariable control techniques to study their behavior. The analysis will give insight into the control design limitations and provide guidelines for the necessary controller structure and system re-design.

2 Literature Review

2.1 Fuel Cell Operation, Subsystems and Parameters

In a (Proton Electron Membrane)PEM fuel cell stack, chemical energy from the reaction between hydrogen and oxygen is converted directly into electric energy. Water and heat are produced as by-products [4].

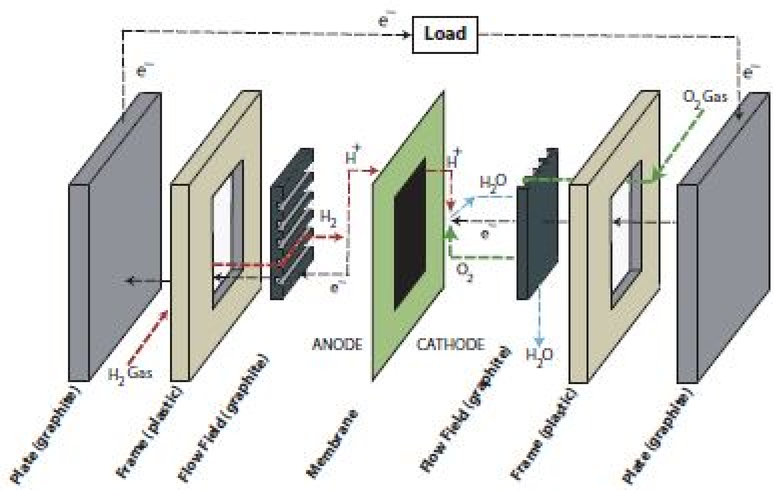

Figure 2.1: Fuel cell component description [2]

In a hydrogen fuel cell, hydrogen (which we will also refer to as fuel) travels through inlet manifolds to the flow fields. From the flow fields, gas diffuses through porous media to the membrane. The membrane, which is sandwiched in the middle of the cell, contains catalyst and microporous diffusion layers along with gaskets as a single integrated unit. One side of the membrane is the anode and the other is the cathode. The anode and cathode are more generally referred to as electrodes. The catalyst layer at the anode separates hydrogen molecules into protons and electrons [2].

$$2H_2 \rightarrow 4H^+ + 4e^- \tag{2.1}$$

The membrane permits only the transfer of hydrogen protons, requiring the electrons to flow through an external circuit before recombining with protons and oxygen at the cathode-to form water.

$$O_2 + H^+ + 4e^- \rightarrow 2H_2O \tag{2.2}$$

The migration of electrons produces electricity. The overall reaction of the fuel cell is:

$$2H_2 + O_2 \rightarrow 2H_2O + Heat. \tag{2.3}$$

The electrical characteristics of fuel cells are given in the form of a polarization curve, shown in Figure 2.2 , which is a plot of cell voltage versus cell current density (current per unit cell active area) at different reactant pressures and flows.

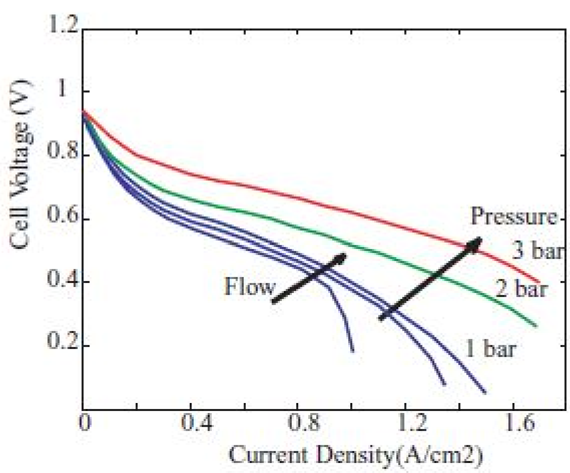

Figure 2.2: Fuel cell component description [2]

Stack temperature and membrane water content affect the fuel cell voltage [9]. The difference between the actual voltage and the ideal voltage represents the loss in the cell which turns into heat. (The ideal standard voltage for a fuel cell in which H2 and O2 react is 1.18 V when the resulting water product is in gaseous form.)

As more current is drawn from the fuel cell, the voltage decreases, due to fuel cell electrical resistance, low reaction rate and, inefficient reactant gas transport,. Lower voltage indicates lower efficiency of the fuel cell, therefore low load (low current) operation is preferred. Operation at low load requires a large fuel cell stack and has detrimental consequences to the overall volume, weight, and cost.

To avoid over-sizing the FC stack, a series of actuators such as valves, pumps, blowers, expander vanes, fan motors, humidifiers and condensers are used to control critical FC parameters for a wide range of current, and thus, power setpoints. The auxiliary actuators are needed to make fine and fast adjustments to satisfy reliability standards, performance and safety that are independent of age and operating conditions of the FC. The resulting multivariate design and control synthesis task, also known as balance of plant (BOP), is complex because of subsystem interactions, conflicting objectives, and lack of sensors.

Main Control among the main FC subsystems are:

- reactant supply system
- heating and cooling system
- humidification system
- Power management System

The main control variables in FC systems are:

- Stack temperature
- Membrane humidity
- Accumulation of water and nitrogen in the anode side.

These variables are the most important factors for any efficiency and lifetime of FC stacks.

Previous research has concluded that since the fuel cell is a passive power source, a simple feed forward control strategy is used to control the air supply and A PI-feedback algorithm is developed to control the cooling water temperature. The research further concludes that the control strategies need to be further optimized basing on a nonlinear dynamic model.

Dr. J.T. Pukrushpan et al.[1] studied modelling and control for PEM fuel cell stack systems, and published several papers. They proposed a nonlinear dynamic model to describe the PEM fuel cell system, and designed feedback controllers based on the model.

Further, there have been efforts devoted in controlling the reactant flow system in PEMFCs using only voltage and current measurements and inferring power. More specifically, a single-input single-output (SISO) controller between the compressor motor voltage and the delivered current or power to the traction motor. Temperature control in available systems is done using large radiators. As a control mechanism to prevent anode flooding, various ingenious mechatronic solutions have been proposed to abate anode flooding (Rodatz et al., 2002) [2].

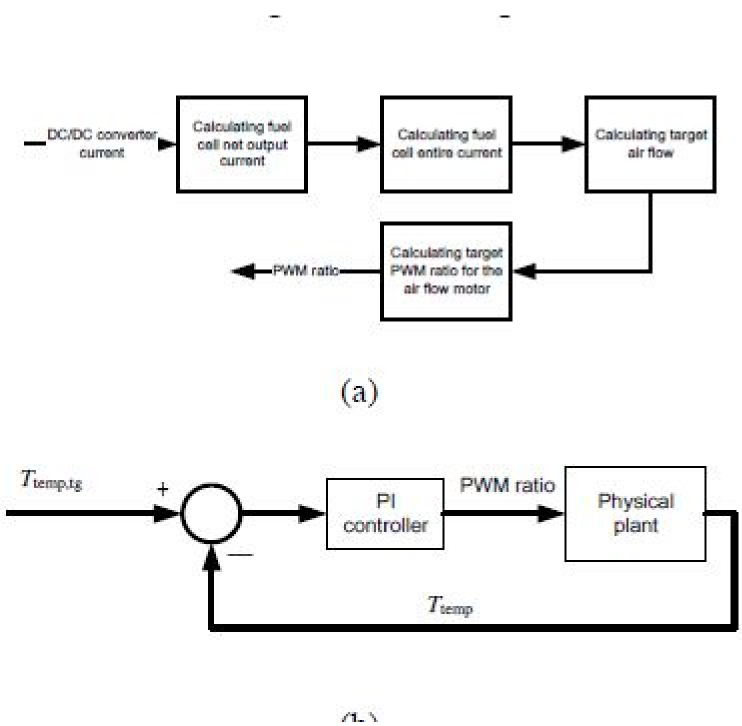

Figure 2.3: Fuel cell control strategy (a) the air supply system (b) the heat management system [3]

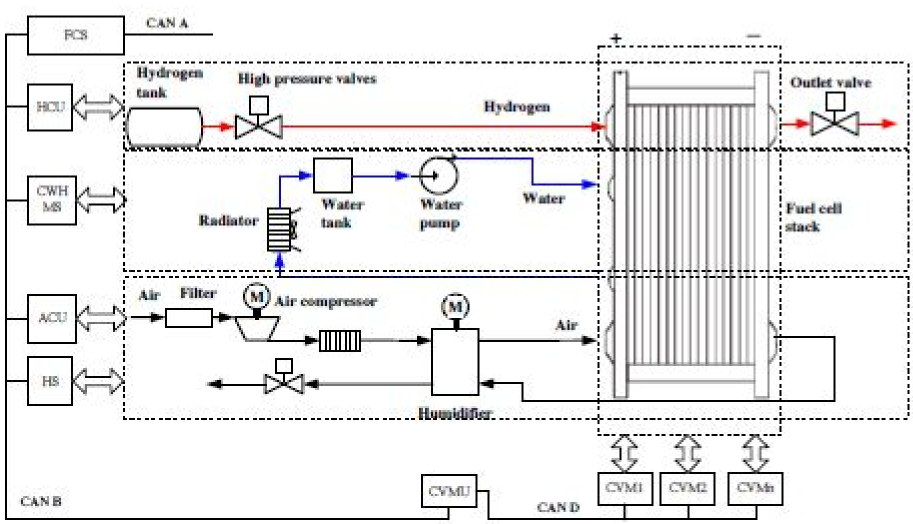

Figure 2.4: Hydrogen Fuel Cell Control [3]

2.2 Fuel Cell Control

The Fuel cell consists of a hydrogen supply system, a water and heat management system and an air supply system. The compressed hydrogen is stored in several tanks, under pressures of about 30 MPa. The hydrogen pressure is lowered and kept at a stable level using several valves for safety purposes before the hydrogen goes into the stack. Water accumulates in the stack due to the electrochemical reaction during the operation of the fuel cell, which leads to performance decay. An outlet valve is installed so that the accumulated water can be blown away with hydrogen. The outlet valve and the hydrogen valves used for lowering and stabilizing the pressure are controlled by the Hydrogen Control Unit (HCU).

The electro-chemical reaction also generates heat, and causes the temperature to increase. The water and heat management system targets to control the stack temperature within a suitable range using deionized water in a water tank. The water flow is controlled by a water pump. The water goes into the stack with a low temperature, and comes out of the stack with a high temperature. A radiator is used to cool the warm water.

The cooling water temperature is measured, and controlled by a feedback control algorithm. The air supply system comprises an air filter, a compressor and a humidifier. The impurities in air will cause the catalyst to be poisoned. Thus as a preventive measure, the air should be filtered before getting into the stack. The air flow is controlled by the compressor with a feed forward + feedback algorithm.

The air is further humified since there should be some water in the PEM, to allow the PEM to conduct protons. In the humidifier, the dry air is humidified with the damp-heat air out of the stack. The air compressor and the humidifier are controlled by the Air Control Unit (ACU) and the Humidifying System (HS).

2.3 Summary

A fuel cell system integrates many components into a power system. These include DC/DC converters, batteries, and ultracapacitors in the system. In cases where the fuel cell is not fed directly with hydrogen, a reformer must be included. Therefore, there are many control loop schemes, the number of which depends on the configuration of the system.

Many control strategies have been proposed in literature, ranging from feed-forward control,Linear quartertic regulator, Neural Networks and Model Predictive Control. A good number of research papers focus on the low level control of the fuel cell to fulfil at least one of the three main objectives such as maximum efficiency, voltage control and/or starvation prevention. However, these designs are still at the theoretical stage and without real time testing. This leads to a methodological gap in the area of hydrogen fuel cell control. The validity of these control strategies for real fuel cell system applications is, however, still under investigation.

Furthermore, the extensive studies in the controller design methods are evidence that the fuel cell system control is a very active research area. The research in this area is mainly motivated by the recognition that the current control methods cannot fully meet the desired design requirements on fuel cell system performance, stability, and robustness etc. Any controller design which gives a satisfactory performance on fuel cell system behavior is worth consideration for implementation [9].

3 Methodology

3.1 System Modelling

The fuel cell system model will be obtained from governing equations from which a transfer function will be generated from the linearized model. The transfer function will be used to generate a state space model for the system.

The system will then be represented in matlab and the controllers designed will be tested on the system to observe the effectiveness of each control method.

Two genral types of models are used in simulation of fuel cell technology, the approaches are detailed lumped parameter dynamic models and black-box models based on system identification. The black box model commonly expresses as NARX (Nonlinear Auto Regressive with eXogenous input) or ARMAX (Auto Regressive Moving Average with eXogenous input) equations. This project addresses both modelling approaches by presenting an ARMAX model for the black-box modelling approach and a detailed mechanistic model for the dynamic modelling approach.

3.1.1 ARMAX Model

Hydrogen is an input variable and is fed at an adjustable flow rate N_H as well as oxygen expressed as n_A derived from air. Voltage and current are the system outputs. Franklin et al [10], represent this as Multiple Input Multiple Output (MIMO) System as shown in the Figure 3.4 below.

The relationship between the inputs (N_A and N_H) and the outputs (I_c and V_c), while R represents the internal resistance. The system can be represented using the following

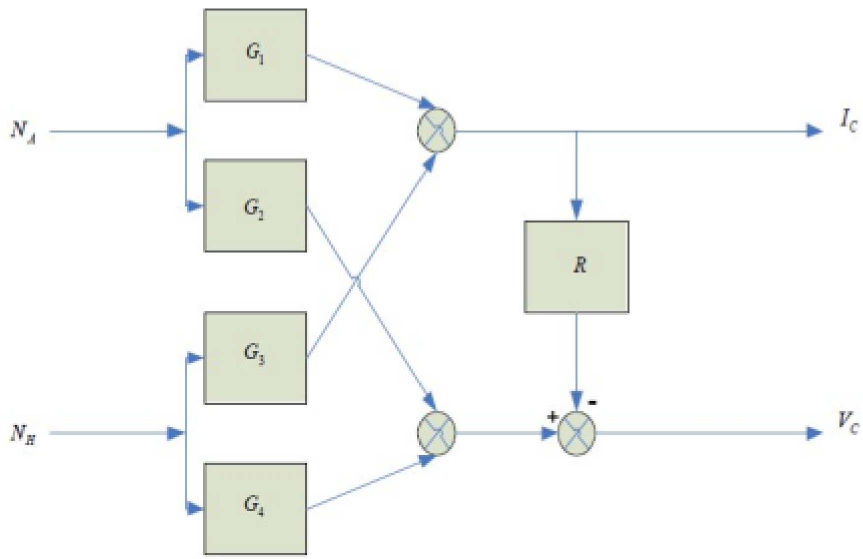

Figure 3.1: MIMO representation of fuel cell [4]

equations:

$$V_c = G_2 N_A + G_4 N_H + R I_C \tag{3.1}$$

$$I_C = G_1 N_A + G_3 N_H \tag{3.2}$$

Equation 3.1 and 3.2 will be used as a basis for system identification and controller design.

3.2 Simulations

From the generated models on matlab, simulations will be performed using the different controllers and the responses and other metrics will be plotted out for further analysis. Metrics such as rise time, settling time and stochastic response will be observed to determine the system performance.

3.3 Sensors

Sensors will be used to collect data from the system as it runs. These include:

- Humidity sensor
- Temperature sensor
- Flow rate sensor
- Pressure sensors
- Voltage sensor
- Current sensor

These sensors will be used by the controller to observe system performance and optimize for each parameter as well as the performance requirements.

3.4 Data Analysis

The data collected from the simulations and sensors will be analysed using custom software created using jupyter notebooks. Graphs will be generated to compare the performance of each controller and evaluation of the selected controller.

4 Expected Outcomes

1. A functional hydrogen stack will be developed and tested

2. The controller for the hydrogen fuel cell will be developed and tested from a selection of controllers that were modelled and simulated.

3. The controller supporting circuitry will be developed with a custom printed circuit board.

4. Hydrogen fuel cell system performance will be optimized using the controller.

5 Proposed Budget

Item	Quantity	Price
Assembled PCB microcontroller (PIC)	1	10,000
Tough PLA filament for case	2	12,600
Micro precision current sensor	1	200
Pressure transducer	2	6,000
Total		28,800

Table 5.1: Proposed budget

6 Work Plan

Year	2021						2022					
Month	DEC	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEPT	NOV	DEC
Literature Review												
Proposal Refinement												
System Modelling												
Controller modelling												
Simulation												
Fabrication and Testing												
Data Collection and Analysis												
Final year report preparation and submission												
Presentation												

Table 6.1: Workplan table

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