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

Final year proposal (FYP 18-10)

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Declaration

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Contents

Declaration	I
Table of Contents	II
List of Figures	IV
List of Tables	V
List of Abbreviations	VI
Abstract	VI
1 Introduction	1
1.1 Background	1
1.1.1 Stewart Platform	1
1.1.2 Wind Tunnel	2
1.1.3 Force Balances	7
1.2 Problem statement	8
1.3 Objectives	10
1.4 Justification of the study	10
1.5 Objectives	10
1.5.1 Main Objective	10
1.5.2 Specific Objectives	10
2 Literature Review	11
2.1 Fuel Cell Operation, Subsystems and Parameters	11
2.2 Fuel Cell Control	16
2.3 Summary	17
3 Methodology	18
3.1 System Modelling	18

3.1.1	ARMAX Model	18
3.2	Simulations	19
3.3	Sensors	20
3.4	Data Analysis	20
4	Expected Outcomes	21
5	Proposed Budget	22
6	Work Plan	22
	References	23

List of Figures

Figure 1.1	General arrangement	1
Figure 1.2	Diagram of a typical wind tunnel	3
Figure 1.3	NASA wind tunnels used to test new airplane designs	4
Figure 1.4	NASA wind tunnels used to test new airplane designs	5
Figure 1.5	NASA wind tunnels used to test the design of heavy-lift rocket . . .	6
Figure 1.6	Typical configurations for external force balances	8
Figure 1.7	Typical configurations for external force balances	9
Figure 2.1	Fuel cell component description [1]	11
Figure 2.2	Fuel cell component description [1]	12
Figure 2.3	Fuel cell control strategy (a) the air supply system (b) the heat management system [2]	15
Figure 2.4	Hydrogen Fuel Cell Control [2]	15
Figure 3.1	MIMO representation of fuel cell [3]	19

List of Tables

Figure 5.1	Proposed budget	22
Figure 6.1	Workplan table	22

Abstract

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

This project will look into the modeling, simulation and development of a Stewart platform based force balance for a small low speed wind tunnel. The project will utilize matlab/ simulink for modeling and simulation as well as autodesk inventor for the mechanical design. A robust control system will also be developed for the Stewart platform. Finally 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 coefficients using a beespoke computer program.

1 Introduction

1.1 Background

1.1.1 Stewart Platform

A Stewart platform is a platform with six degrees of freedom (DOF). The six-degrees-of-motion platform is capable of moving in three linear directions and three angular directions singly or in any combination. It comprises a triangular/rectangular/circular plane called the platform, of which each of the corners (for triangular platform in this case) is connected through a three-axis joint to one of three legs. This is shown in Fig.1.1.

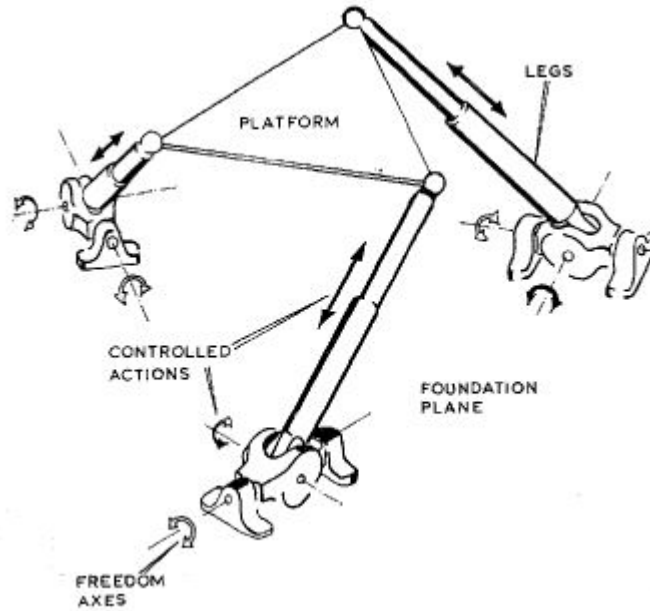


Figure 1.1: General arrangement

Each leg is connected to the ground by a two-axis joint where: One of these axes is normal to the leg and is provided with a means for control whereas, the other axis

is normal to the first and is not provided with a means for control. Each leg also has controllable means for extending its length. These control means include:

1. Use of two hydraulic jacks
2. Screw Jacks
3. Rotary actuator
4. Levers
5. Linear co-ordinate control
6. Strength

These shall be discussed in detail at a later stage.

Application

The six DOF Stewart Platform provides an elegant design for simulating flight conditions which finds applications in the safe training of pilots. The mechanism differs from other simulators in that it has no fixed axes relative to the ground, and therefore within the limits of amplitude of the design it can truly simulate the conditions of banking by carrying the simulation of control surfaces into the axes of the new attitude.

1.1.2 Wind Tunnel

A wind tunnel is a large tube with air moving inside. This movement of air is usually done by powerful fans. The tunnel is used to copy the actions of an object in flight thus allowing to obtain the components that better define this interaction, forces and moments.

The first wind tunnel was built by Francis Wenham in 1871. However, it was the Wright Brothers who were the first to show the value of the wind tunnel in aerodynamic design with their 1902 wind tunnel. The Wright Brothers' wind tunnel was largely made of wood, with a glass window on the top to look down through and see the force balance, from which the lift and drag forces could be read. The wind tunnel was powered by a fan driven off a natural gas fueled engine. Their tunnel was square of 16" by 16" (about 407mm by 407mm), and 6 foot long (about 1829mm), with a maximum test speed of 35 mph (about 56 km/h).

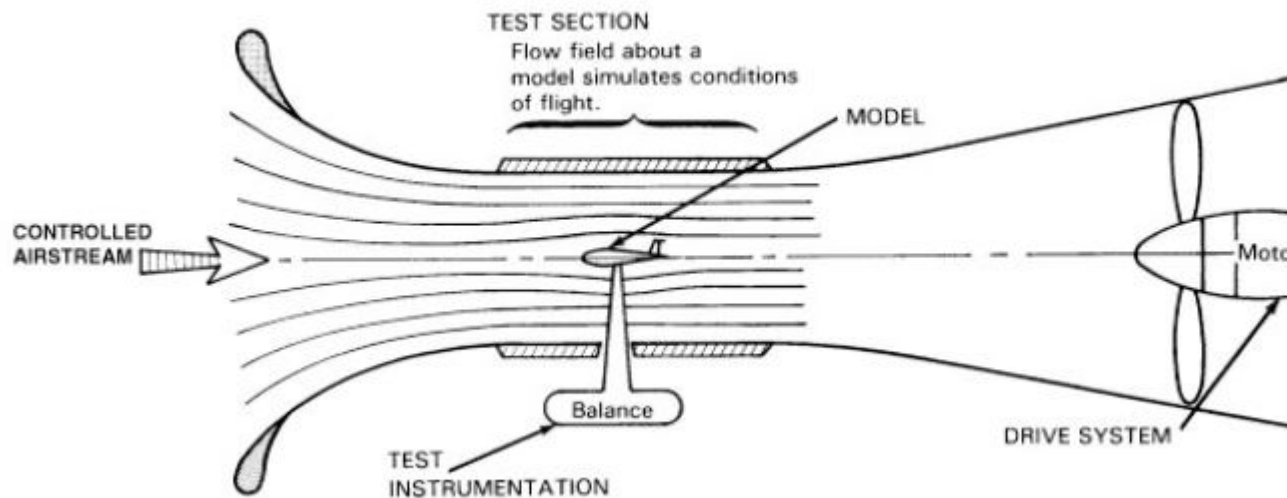


Figure 1.2: Diagram of a typical wind tunnel

Later in the early 20th century in Europe, the main users of wind tunnels were Gustave Eiffel in France and Ludwig Prandtl in Germany. Prandtl built the first closed circuit wind tunnel in 1908.

Closed circuit wind tunnels are characterized by the recirculation of the airflow with very minimal exchange with the exterior. Open circuit wind tunnels on the other hand, have an airflow that follows a straight path and flows to the contracted zone where the test section is located and then passes through a diffuser, a fan section and an exhaust. [4] By the 1940's supersonic wind tunnels were in use. In 1972 a cryogenic wind tunnel was built at NASA Langley by injecting liquid nitrogen into the wind tunnel to cool the gas. This lowered the viscosity and increased the Reynolds number, and this tunnel had the capability to match Reynolds and Mach numbers simultaneously up to Mach 1.2.

Today the largest wind tunnel in the world is the National Full-Scale Aerodynamics Complex at NASA's Ames Research Center, which has a test section of cross section 80 ft by 100 ft (24 m x 31 m). The types of instruments in common use in wind tunnels include boundary layer rakes, tufts, pitot tubes, pressure sensitive paint, smoke, and static pressure taps.



Figure 1.3: NASA wind tunnels used to test new airplane designs

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Figure 1.4: NASA wind tunnels used to test new airplane designs

NASA uses wind tunnels to test scale models of aircraft and spacecraft. Wind tunnels help NASA to test ideas of making airplanes better and safer. They are also used to help engineers in designing spacecraft that will work in other planets such as mars - the wind tunnel can be used to simulate objects in an atmosphere that's thinner than ours

i.e. an atmosphere that's exactly like the Martian atmosphere. NASA has wind tunnels of different types and sizes. Some are low-speed wind tunnels, others are hypersonic i.e. they are made to carry out tests at 4,000 mph (6437 kph).



Figure 1.5: NASA wind tunnels used to test the design of heavy-lift rocket

Wind tunnels are used to measure the aerodynamic forces on airplanes, wings, cars, trucks, bridges, and buildings, they can also be used to measure the aerodynamic forces on sports balls, partially open valves, and anything else that can be mounted on the mounting sting. Wind tunnels are an effective tool used by engineers in determining the various aerodynamic loads due to movement of these vessels during the development process. For wind tunnel testing with scale models to be applicable to the aerodynamics of the full-scale test object, conditions of dynamic similarity must be met.

Wind tunnel testing is not cheap i.e. both to build and to use. While a crude wind tunnel can be constructed relatively cheaply from a large fan and sheet metal, our project will be limited to development of the six-degrees-of-freedom Stewart Platform and Force balance. We will use the low speed wind tunnel that is currently available at the fluids laboratory.

1.1.3 Force Balances

A force balance is a device used to take direct measurement of forces and torques acting on the model that is being tested in the wind tunnel. The need for force balances arises due to the necessity of having maximum load capability in all measuring components along with the accuracy for measuring minimum loads. Force balances can be external or internal. In external force balances the test section lies outside of the wind tunnel test section, whereas in internal force balances the balance is inside the model itself connecting the model to the support structure. [4]

Several different types of external force balances are available for wind tunnel use [5]:

1. Wire
2. Platform
3. Yoke
4. Pyramidal

The different kinds of internal balances can be made based on: 1 the type of transducer i.e. strain gauge or piezoelectric balance. 2 shape i.e. box balance and sting balance

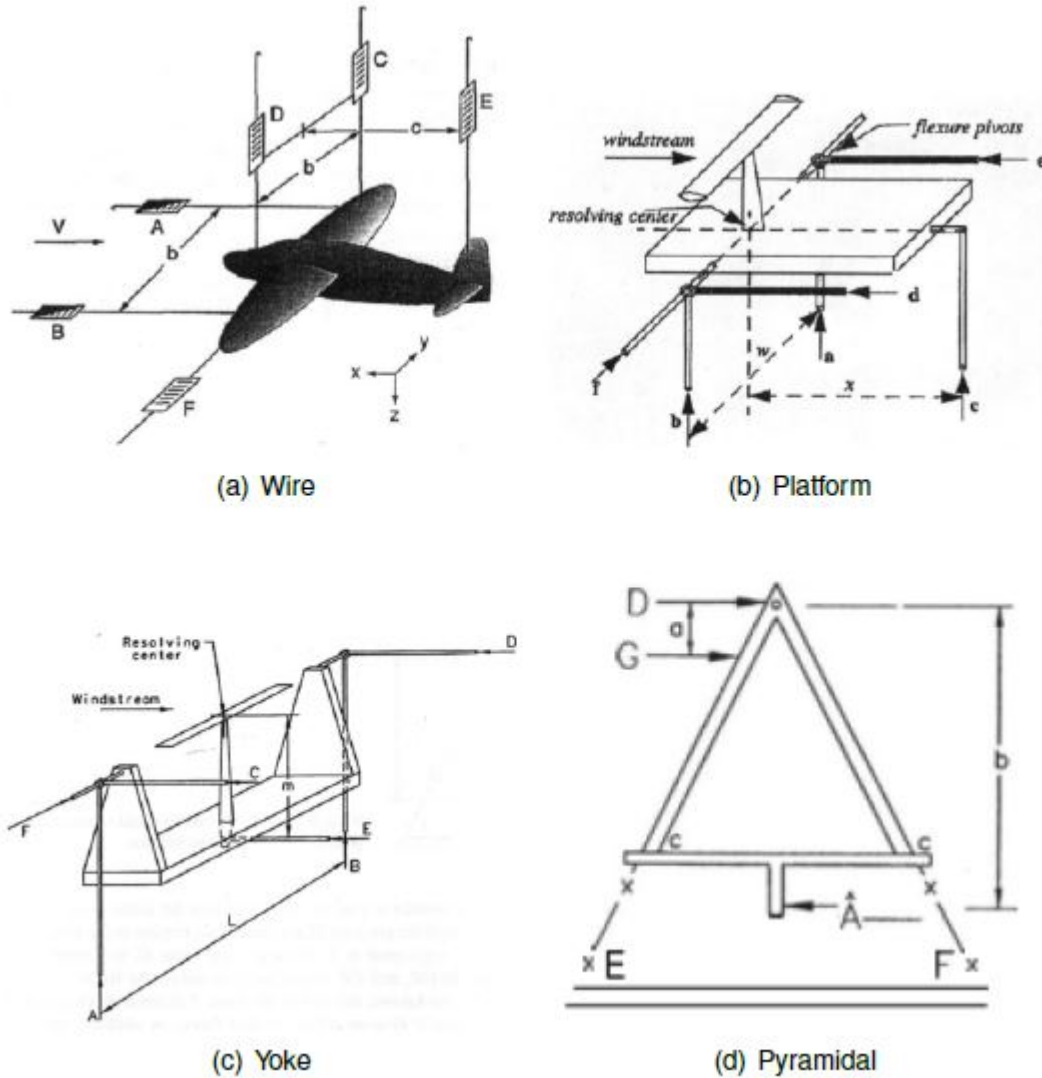


Figure 1.6: Typical configurations for external force balances

1.2 Problem statement

Simulation and analysis of scaled models is an important step in the development of aircrafts, vehicles and other machines . Such analysis provides aerodynamic performance data that can be used to inform any modifications or improvements e.g. in aircrafts and vehicles to make them more efficient and safer. One such method that is used to perform aerodynamic performance evaluation is the wind tunnel, which can be low speed or high



Figure 1.7: Typical configurations for external force balances

speed, used in conjunction with sensors for data acquisition by a computer. External or internal six-component force balances are also used. Another such technology that can be used for this purpose is the Stewart platform, which can be used to predict behaviour of vehicles and aircrafts in the actual environment.

Whereas the wind tunnel gives very accurate results, it is expensive to build and use. Also, some objects require complex maneuver simulations to imitate the actual movements in air. There is therefore the need for dynamic positioning of objects in the wind tunnel.

This project proposal, therefore, presents the development of a 3-component external force moment-balance to stand as a simple and economical alternative to the existing commercial solutions. The force balance should be able to measure lift, drag and pitching moment in small models and will be used with a generic low speed wind tunnel which is already available. The proposal also presents the design of a six-degrees-of-freedom Stewart platform to simulate the different movements of objects.

1.3 Objectives

1.3.1 Main Objective

1. To develop an external Stewart platform force balance for a low speed wind tunnel

1.3.2 Specific Objectives

1. To design and fabricate a six-degrees-of-freedom Stewart platform
2. To develop a force balance for the Stewart platform
3. To obtain forces and moments from a test model

1.4 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.

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 [3].

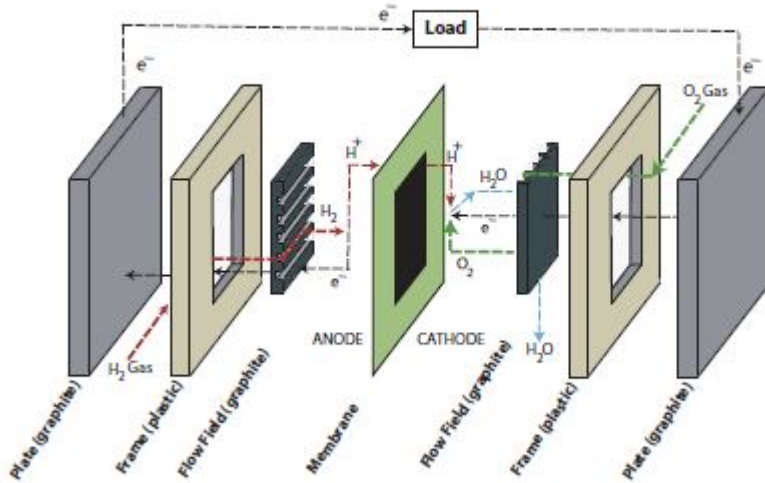


Figure 2.1: Fuel cell component description [1]

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 [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.



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



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.

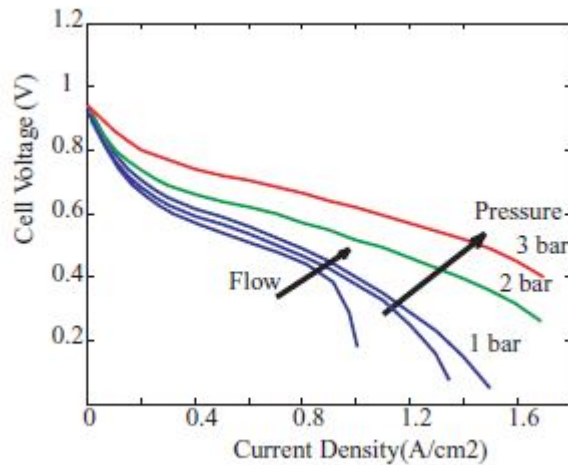


Figure 2.2: Fuel cell component description [1]

Stack temperature and membrane water content affect the fuel cell voltage [6]. 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.[7] 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 PEM-FCs 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) [1].

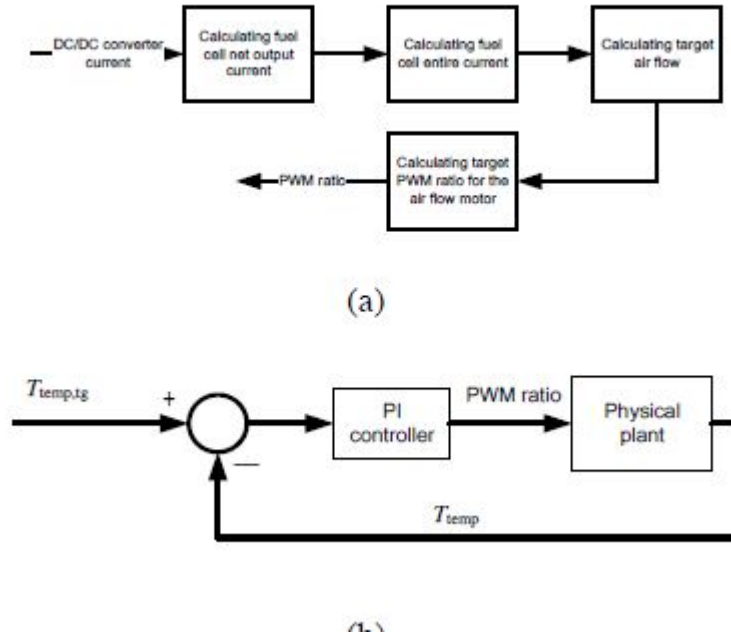


Figure 2.3: Fuel cell control strategy (a) the air supply system (b) the heat management system [2]

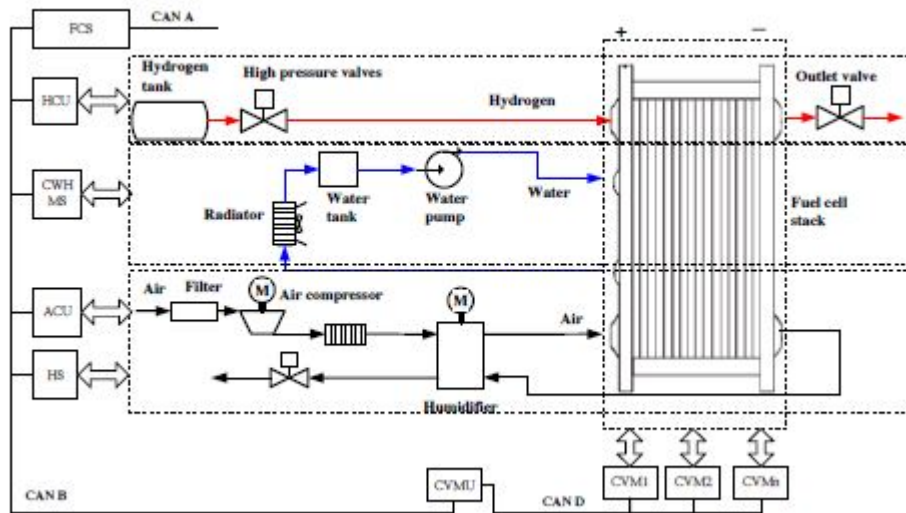


Figure 2.4: Hydrogen Fuel Cell Control [2]

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 quadratic 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 [6].

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 [8], 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

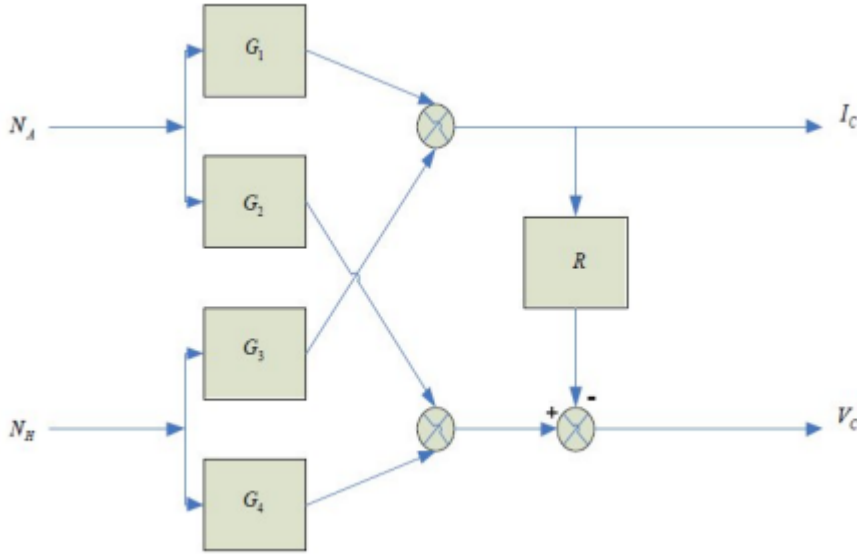


Figure 3.1: MIMO representation of fuel cell [3]

equations:

$$V_c = G_2 N_A + G_4 N_H + R I_C \quad (3.1)$$

$$I_C = G_1 N_A + G_3 N_H \quad (3.2)$$

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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