Jomo Kenyatta University of Agriculture and Technology

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 proposal (FYP 18-10)

Sammy Kerata Oina (ENM221-0089/2017)

Earl Spencer Mogire (ENM221-0074/2017)

June 2, 2022

Declaration

We hereby declare that the work contained in this report is original; researched and documented by the undersigned students. It has not been used or presented elsewhere in any form for award of any academic qualification or otherwise. Any material obtained from other parties have been duly acknowledged. We have ensured that no violation of copyright or intellectual property rights have been committed.

1. Sammy Kerata Oina

   Signature............................Date............................

2. Earl Spencer Mogire

   Signature............................Date............................

Approved by supervisors:

1. Ir. Anthony K. Muchiri

   Signature............................Date............................

2. Ms. Maurine Andanje

   Signature............................Date............................

Contents

List of Figures

List of Tables

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). It comprises a triangular/rectangular/circular plane called the platform, of which each of the attachments to the platform is connected through a three-axis joint to one of three legs. A Stewart platform is shown in Fig.1.1.

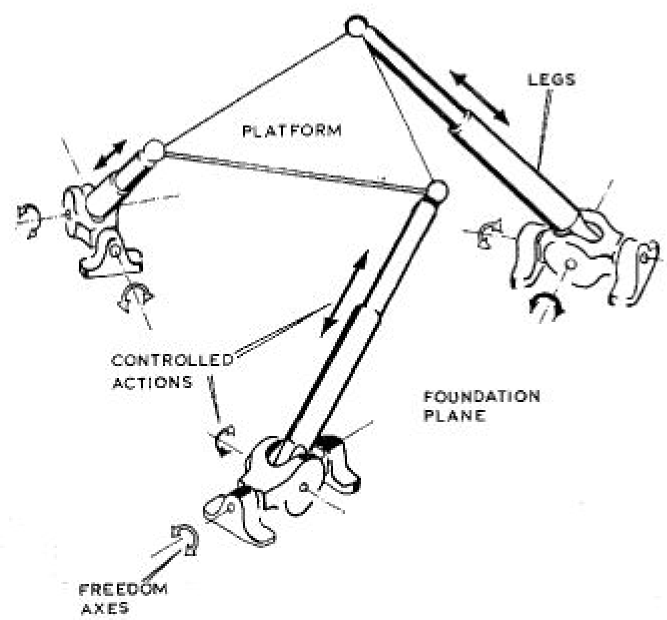


Figure 1.1: General arrangement

Each leg of the Stewart platform is connected to the ground by a two-axis joint and is provided with controllable means for extending its length.

Application

The six DOF Stewart Platform provides an elegant design for simulating flight conditions that can be used in safe training of pilots.

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).

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. 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. [2]

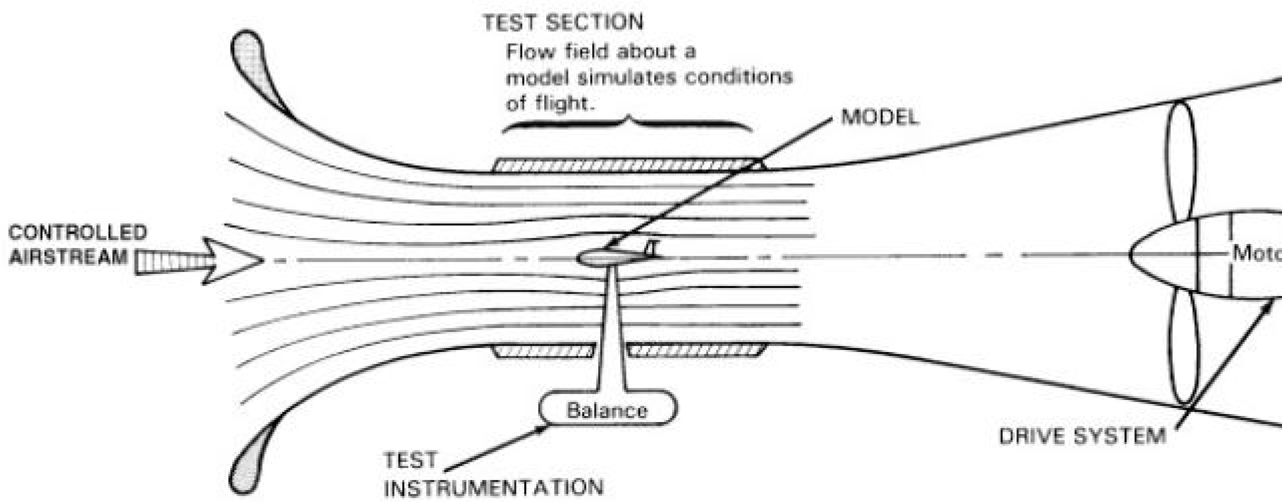


Figure 1.2: Diagram of a typical wind tunnel

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.

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 e.g. 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 1.3: NASA wind tunnels used to test new airplane designs

Figure 1.4: NASA wind tunnels used to test the design of heavy-lift rocket

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 Balance and Load Sensors

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. [2]

The force balance is intended to be built as simple and accessible as possible. Thus, the development of a three-component balance will be considered.

Several load measurement devices have to be connected to the main structure in order to measure and obtain the results and so making it fully operational. This project looks to employ electrical load measurement techniques. Strain gauges will be used.

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 peformance 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 speed, used in conjuction with sensors for data aquisition 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 movemnets of objects.

1.3 Objectives

1.3.1 Main Objective

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 Stewart Platform

Parallel link manipulators have become an important area of research due to their: precision, rigidy and high-load-to-weight ratio. These manipulators find practical applications in flight simulators, precise machining and applications that require distutbance isolation. [**?**]. The Stewart platform is an example of a parallel manipulator.

A Stewart platform [3] is a parallel manipulator that provides six-degree-of-freedom (6DOF) i.e. roll, pitch, yaw, surge, sway and heave, and can be controlled in all these freedoms simultaneously. The platform consists six variable-length electro-mechanical actuators connecting a top plate to a base plate with spherical joints.

The platform is able to move in three angular directions and in three linear directions, singly or in any combination [3]. Angular and translational motion of the top plate with respect to the base plate is acheived by reducing or extending the actuator lengths. For the top plate to follow the desired trajectory with high frequency, there has to be proper coordination of the actuator lengths [**?**].

Each leg of the mechanism 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 hydraulic jacks.

2. Screw jacks - This gives give the advantage of a longer stroke for a given size.

3. Rotary actuator - a hydraulic rotary actuator or an electric motor. Whereas this would reduce the number of foundation fixings, the remaining jack would still be subjected to a greater bending moment.

4. Levers - this increases the extending leg amplitude by using an articulated leg.

5. Linear co-ordinate control - this arrangement provides rigidity due to the true triangulation of the whole system. There will be no bending moments in any of the members apart from the possibility of those due to strut eccentric loading.

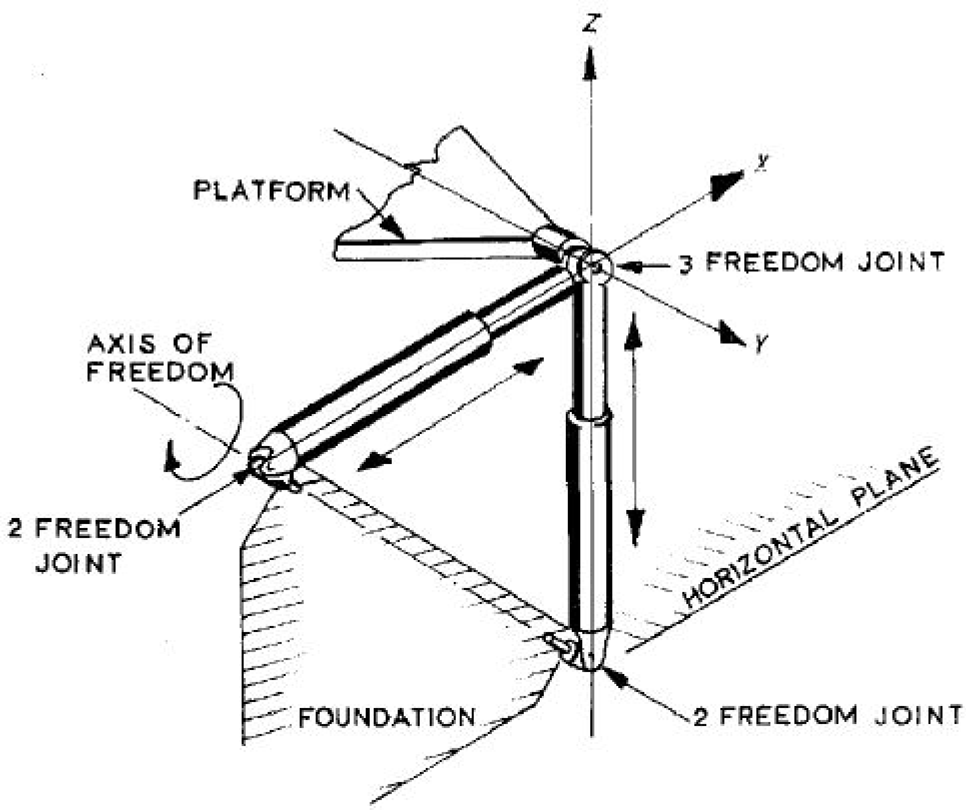


Figure 2.1: Linear co-ordinate control

Stewart platforms that use screw jacks driven by electric motors as leg actuators have the advantage of being light and easy to control. Velocity and position control for these platforms can be done using shaft encoders and tachometers. A ball screw is used to minimize friction in a screw drive and backlash in the ball screw can be eliminated by use of double nuts preloaded with spring washers [**?**].

In order to control the platform in the required direction, a program involving linear or angular accelerations or a combination of both is necessary so that signals can be given to the various legs in accordance with the input requirements. The six inputs to the Stewart platform in terms of torque are calculated by the controller and the outputs of the Stewart platform are the upper plate's angular and translational positions sensed by highly precise sensors or estimated by the motor's encoders [**?**].

Further, as concerns the control aspect, in recent years many researchers have worked on robust controllers for the Stewart platform. Some of these works include:

1. A Lyapunov based approach for designing robust PD controller was proposed in presence of uncertainties [4].
2. The model based sliding mode control with perturbation [4].
3. Robust tracking control design in the presence of time varying uncertainties [5].
4. Tracking errors drive to zero asymptotically with help of sliding mode controller design [6].
5. A simple way to calculate control law using sliding-mode technique [7].

2.2 Force Balances

For wind tunnel applications, the wind axes is used as the reference frame. Where, X axis points to the accelerated air; Z axis points downward and; Y axis points to the right in the direction of the wind. In the reference frame above, lift is in the negative z-direction, drag in the negative x-direction and, side force in the negative y-direction.

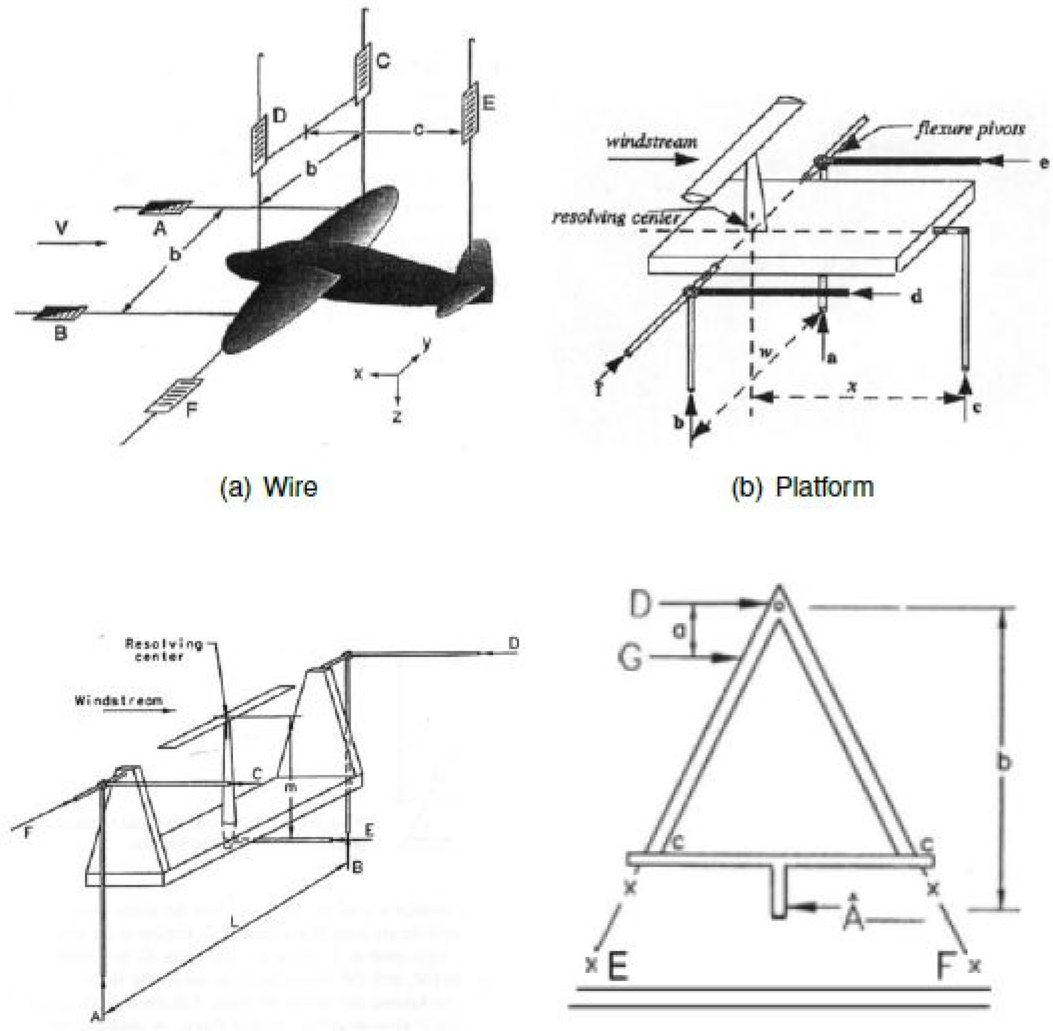
Moment components on the x,y,z axes are rolling moment, pitching moment and yawing moment respectively. A three-component force balance can be considered to measure the lift, drag and pitch (angle of attack).

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.

Several different types of external force balances are available for wind tunnel use [8]:

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

In the wire balance, the model under testing is suspended by wires each connected to an extensometer (a sensor that produces an electrical output when submitted to a load and deforms). The shortcoming of the wire balance is the large tare drag caused by the wires which is difficult to quantify. They are also not robust nor versatile enough compared with the other alternatives.



(a) Wire (b) Platform

(c) Yoke (d) Pyramidal

Figure 2.2: Typical configurations for external force balances

The platform balance is relatively easy to construct, assemble and instrument. However, for this balance, forces and torques are coupled and the balance resolving center does not coincide with the center of the tunnel.

In the yoke balance configuration, forces and torques are coupled and the balance resolving center coincides with the center of the tunnel. This configuration, however, presents some structural deflections due to the large span of the measuring and support arms.

The pyramidal balance configuration is a further improvement of the yoke balance in order to overcome the shortcomings of the other balances. It is capable of measuring six components of forces and torques separately and without coupling,provided that the balance is well assembled and calibrated.

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

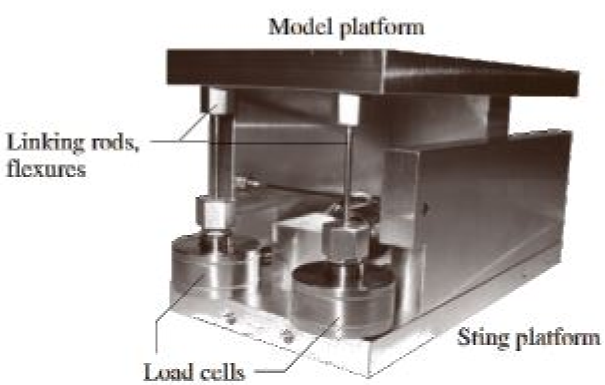


Figure 2.3: Typical configurations for internal force balances. *Left to right:* Box balance and sting balance.

The box balance presents a cubic shape and can either be made of a solid piece of material or from assembled parts. In this configuation, the loads are transferred from the top to the bottom. The sting balance presents a cylindrical shape and the loads are transferred from one end to the other in the longitudinal direction. It can be used to measure forces or torques.

The advantage of internal force balances is that they minimize the interference caused by the supporting bars in the flow.

2.3 Sensors

2.3.1 Load Sensors

Several methods can be used to measure forces and torques in a force balance. These methods can be generally grouped into two:

1. Hydraulic measuring techniques.
2. Electric measurement techniques.

Electric measurement techniques are preferred for Force balance applications. One such electric measurement device is the strain gauge. A strain gauge is an electromechanical device whose electrical resistance changes linearly with the strain in the component.

Metal foil strain gauges are widely used. This type of strain gauge provide more precise strain values than wire strain gauges. However, since the relative changes on electric resistance of the strain gauge are so small, it is necessary to develop an effective method to measure them because each strain gauge would require extremely accurate signal measurements. The solution is to have a set of strain gauges coupled in order to minimize the required accuracy, forming a force transducer i.e. the *Wheatstone bridge*.

Load cells can also be used to measure the drag and lift forces.

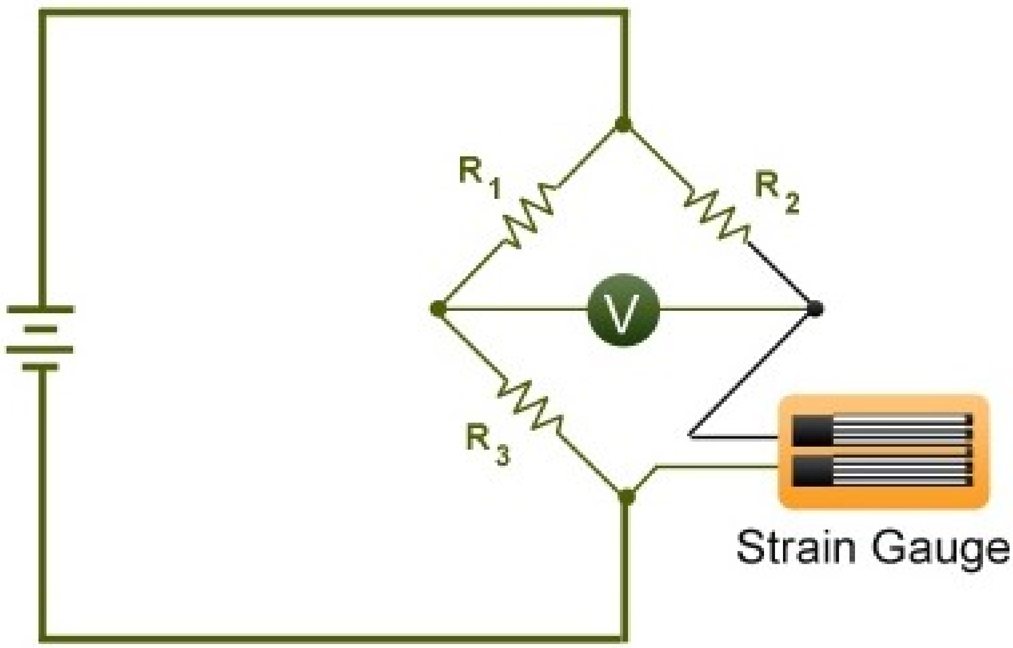


Figure 2.4: Wheatstone Bridge Circuit

2.3.2 Altitude Sensor

It is important to define the desired aerodynamic angles and to guarantee that they are measured accurately in relation to the air stream. One such angle is the angle of attack (α) shown in Figure 2.4. For this reason, specific devices that provide the attitude measurement should be implemented in order to improve the precision of the results.

Angle of attack (α)- angle measured between the longitudinal axis of the model and the direction of the flow on a vertical (Figure 2.4)

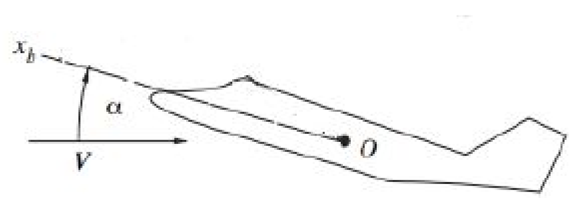


Figure 2.5: Angle of attack (α)

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 [9], 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

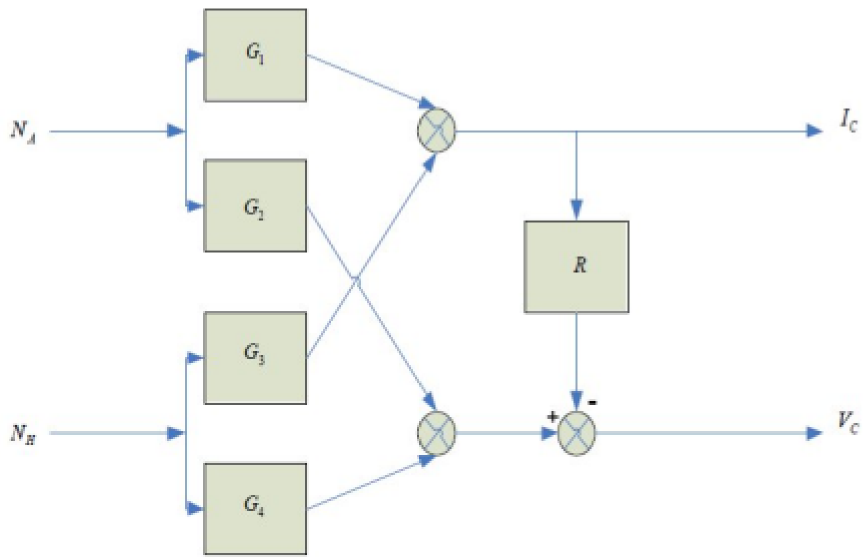


Figure 3.1: MIMO representation of fuel cell [1]

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

References

[1] K. Thanapalan, G. Premier, and A. Guwy, "Model based controller design for hydrogen fuel cell systems," *Renewable Energy and Power Quality Journal*, pp. 671–676, May 2011. [Online]. Available: http://www.icrepq.com/icrepq'11/419-thanapalan.pdf

[2] J. T. P. Fernandes, "Design of a wind tunnel force balance," p. 122.

[3] D. Stewart, "A platform with six degrees of freedom," *Proceedings of the institution of mechanical engineers*, vol. 180, no. 1, pp. 371–386, 1965.

[4] J.-Y. Kang, D. H. Kim, and K.-I. Lee, "Robust tracking control of stewart platform," in *Proceedings of 35th IEEE Conference on Decision and Control*, vol. 3. IEEE, 1996, pp. 3014–3019.

[5] N.-I. Kim and C.-W. Lee, "High speed tracking control of stewart platform manipulator via enhanced sliding mode control," in *Proceedings. 1998 IEEE International Conference on Robotics and Automation (Cat. No. 98CH36146)*, vol. 3. IEEE, 1998, pp. 2716–2721.

[6] C.-I. Huang, C.-F. Chang, M.-Y. Yu, and L.-C. Fu, "Sliding-mode tracking control of the stewart platform," in *2004 5th Asian Control Conference (IEEE Cat. No. 04EX904)*, vol. 1. IEEE, 2004, pp. 562–569.

[7] S. Iqbal and A. Bhatti, "Direct sliding-mode controller design for a 6dof stewart manipulator," in *2006 IEEE International Multitopic Conference*. IEEE, 2006, pp. 421–426.

[8] M. Morris and S. Post, "Force balance design for educational wind tunnels," in *2010 Annual Conference & Exposition Proceedings*. ASEE Conferences, pp. 15.594.1–15.594.10. [Online]. Available: http://peer.asee.org/15891

[9] G. F. Franklin, J. D. Powell, A. Emami-Naeini, and J. D. Powell, *Feedback control of dynamic systems.* Prentice hall Upper Saddle River, NJ, 2002, vol. 4.