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Final report for MSc Project

Design and Development of a High Resolution, Real-Time 2D Force Sensor System for Wind Tunnel Experiments

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Abstract

Understanding aeroelastic phenomena in insect wings can generate insights into the control and management of flexible wings. Such study requires a continuous, high-precision load measurement system to assess various wing structures in a low-speed wind tunnel. This project reviews, designs, and implements a proof-of-concept system. This paper explains a method to detect two different wing forces in the wind tunnel with high frequency (2kHz) and high accuracy (mN), which might be useful for future bio-inspired sensor systems. It will be discussed how this system will be put into the wind tunnel system, how the device will be used for the sensor system, how to cancel torque, increase the sampling rate, cancel noise, factor in drift, and other processing details. I designed an experiment to test whole systems and inspect key points of the result. Future plans of the bio-inspired sensor and future improvements to the plan are also discussed.

1. Introduction

The aeroelastic effect is a phenomenon between the inertial, elastic, and aerodynamic forces which occur while an elastic body flows through a fluid, as described by Ernest Edwin Sechler in 1942. To study this phenomenon, I built equipment to detect the force of wings in a wind tunnel. In recent years, the insect micro aerial vehicle has intensified focus, especially on the dragonfly [1]. Dragonflies can be identified as an effective predator from the earliest fossils from the late Carboniferous period [2]. Their success as a species can be evaluated from a mechanical, physiological, and behavioural perspective. Dragonflies show impressive flying skills that assist in evading hawks and allow them to cross oceans with their energy-efficient flying [3], [4]. All of these flying skills require a complicated sensory system. Like other animals, dragonflies use their sensory feedback to control their body, plan future activities, and accumulate experiences for motor learning. There are 71 muscles in a dragonfly's wings [5]. Many of these muscles attach to the radial veins, which allow active control in the angle of attack, camber, twist, amplitude, and frequency of each of the four wings independently [6]. Flying animals' wings experience inertial-aerodynamic force, airflow stagnation and separation, and the non-linear phenomena of the vortex changing continuously [7]-[9]. The sensors fire signals when the wing strokes, but these signals are not continuous. In the beginning, two different axis forces could be easily detected: the row and yard axis [10]. These axes' force detection will be the main purpose of this project. There is not much research on dragonfly characterising bio-inspired wings, so the main of the sensor target object is characterising bio-inspired wings of dragonflies.

2. Literature review

This literature review will be split into three parts, discussing insect flight, forces in a wind tunnel, and different sensor types.

A. Single support

There are several ways to support a target object within the wind tunnel, such as single support, double support, and central support. The details of these will be covered later in the methodology section, but first, an explanation of why the single support is most suitable when all of the limitations in a wind tunnel are considered. It is a main method being the robotic insect's use of single support regarding direct force on the wing. [10]-[12] describe a force transducer system used in a wind tunnel, which will be the main reference source for our project [10]-[12] and the project's design will be based on publications by Ştefănescu [12], Beyeler et al. [13], and Brookhuis [14].

B. Wind tunnel & Insect flight

There are many different forces on wings. To define them, we use rectangular coordinate system analysis. Twenty years ago, there were many experiments based on wind tunnel tests [15], but in recent years computational fluid dynamics (CFD) has been more frequently used in evaluating wind tunnels. The purpose of CFD was to predict two-dimensional airfoil properties, but in recent years they are also used to simulate different flight environments [15].

There are several methods to test forces on wings in a wind tunnel. Şugar Gabor et al. [15] shows one well-developed CFD method that can be used in a wing simulation. Otherwise, using a force transducer in a wind tunnel is the general method. A fluid flowing around the surface of an object exerts a force on it. Lift is the component of this force that is perpendicular to the oncoming flow direction [15]. It contrasts with the drag force, which is the component of the force parallel to the flow direction. Lift conventionally acts in an upward direction in order to counter the force of gravity, but it can act in any direction at right angles to the flow.

C. Different sensor types of force transducers

Based on the last section, various methods could be used in the wind tunnel system, but the basic force test will read from a strain gauge. This section will introduce different strain gauge types and discuss how to connect them to make a whole Wheatstone bridge. Furthermore, how to amplify the signals will be discussed, and the different methods of reading data from the strain gauge will be explained. This part will extrapolate on the different sensor types that could be used in the wind tunnel to test force [16], [17].

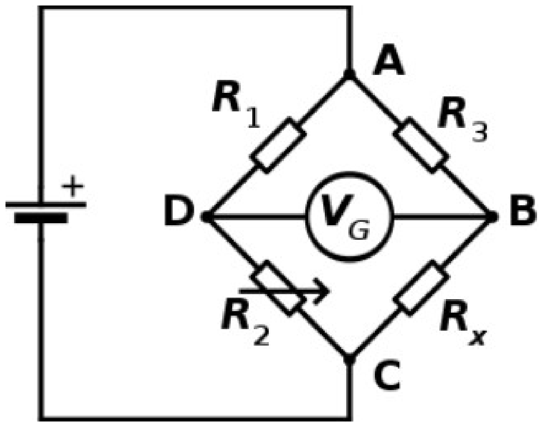

Figure 1. Wheatstone bridge sketch [18]

According to Figure 1, four strain gauges could constitute one load cell and a Wheatstone bridge which is an electrical circuit that uses to provide accurate measurements and increase output [16], [17]. The purpose of the strain gauge is to collect strain from a load cell, then send the signal to the Wheatstone bridge, then the Wheatstone bridge will amplify the signal to be readable. This is a one-dimensional force test unit. There are many other force test units, such as a 3-

axis force transducer and a 6-axis force transducer. They all use a different shape, but most force transducers use the same principle, which is to use a strain gauge to detect small amounts of strain [14], [19].

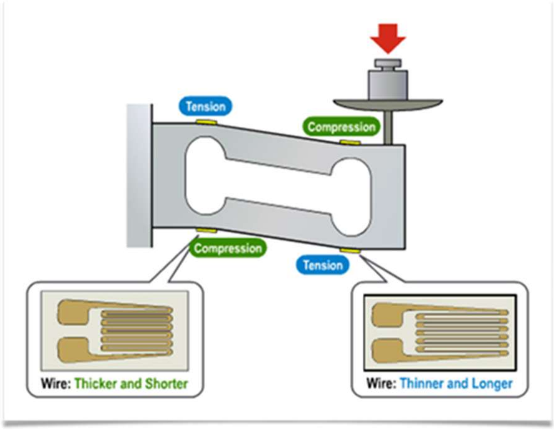

Figure2. Load cell sketch [20]

Figure 2 explains the relationship between sensor and load cell [10].

There are many different types of strain gauge: resistive force transducers [10^{-13} to 10^{8} N], capacitive force transducers [10^{-9} to 10^{4} N], piezoelectric force transducers (PZFT) [10^{-1} to 10^{9} N], and electrodynamic force transducers (EMFC) [10^{-2} to 10^{3} N] [14]. Different force sensors have different benefits and limitations. The resistive force transducers are the most popular of these different sensor types because they can detect a wide range of forces and are easy to use.

The many different sensor types available on the market are discussed and reviewed by articles by Ştefănescu wrote a handbook containing vast information about strain gauges. These sensors were designed based on [12]-[14].

1) Capacitive sensor

Beyeler et al. introduce a new capacitive sensor that uses magnetic force as a medium to measure microscopic torque and force accurately. [13] describes how to manufacture and calibrate capacitive (magnetically based) MEMS sensors. The main limitation of a capacitive sensor is that it is very sensitive to environmental conditions, such as temperature and humidity. In addition, the paper also specifically noted that this design could be applied to bio-inspired micro-robots. MEMS sensors are one of the main sensors used that could detect gram-force, despite their low-cost performance.

2) Piezoresistive pressure sensor

The piezoresistive pressure sensor is also one of the main sensors for measuring force [21]. Its purpose is the opposite of capacitance. The stress applied to the resistive pressure sensor causes the resistance change to be recorded. This process can measure the applied force and strain. The article introduces a resistance sensor that measures minuscule forces, which can be used in future projects. The manufacture of resistance pressure sensors is relatively simple, which has become one of its advantages [21]. However, the resistance sensor needs a Wheatstone bridge to amplify the return result, which leads to a larger size. In addition, resistance pressure sensors will cause errors in measurement results due to temperature changes, therefore, temperature management is required to eliminate errors [21].

3) Resistive strain gauges

Resistive strain gauges are the most common type of force transducer, using multi-dimensional force detection such as a 6-axis force transducer, 3-axis force transducer, and a load cell. The robotics industry developed the 6-axis force transducer—a more commonly used force sensor in recent years. Many companies use resistive strain gauges to build multi-axis force transducers. These could be used in the robotics industry and in the wind tunnel to detect different dimensions of force [12], the limitation of resistive strain gauges is fatigue, amount of strain, and temperature.

D. Summary

To summarise the literature review, we need to investigate a system to detect force characteristic insect wings undergoing aeroelastic deformation in the wind tunnel. Ultimately, we will develop a force sensor system. This force transducer system could be one of the bio-inspired sensors systems or a force detection system. Because a target object could be a dragonfly or bio-inserted robot, the amount of force is minimal, and CFD or other traditional force transducers could not sufficiently detect this low level of force. Therefore, the development of this transducer becomes indispensable. To produce this equipment, I first checked what force transducer is normally used in a wind tunnel, then learned about the different methods and sensor units.

3. Methods

A. Introduction

This project will focus on generating a method to measure the force of the wings from the shoulder. The bio-inspired dragonfly's wing will be tested using the method produced by Pathak. This method could also be used for normal aviation object force detection purposes. This project aims to investigate and improve bio-inspired dragonfly abilities by collecting flight data from the wind tunnel. The wind tunnel mentioned before is a low Reynolds number tunnel designed by Myriam. There are some challenges and differences from past experiments on this project. Foremost, the measuring method. Many present methods could test a wing’s force, but most of them are not suitable for bio-inspired robotic dragonflies. Furthermore, the bio-inspired dragonflies’ Reynolds numbers are much smaller than an aircraft’s, where viscous forces are dominant [22]. Therefore, developing a suitable measuring method becomes necessary for this project.

B. Sources used in literature review and analysis

This method has different resolutions, force detection dimensions, and connection methods. In our project, the first limitation is size, so how to connect the wings becomes a critical issue. There is a table below to explain the advantages and disadvantages of different connection parts.

Figure 3. Different Sensor Support
Type a) Double Support[27] b) Central Support[28] c) Sigle Support[12].

Table 1 Compare Force Transducers

Support type	X	Y	Z	Size	Sensitivity	Reference
One side	Yes	Yes	Yes	5	4	Most of bio-inspired insect robots using this plan. Might influence by torque, need open a whole on the wind tunnel.
Two side	Yes	Yes	No	3	5	This plan cannot be suitable for one side wings connection. Need open two hole of the wind tunnel.
Centre	Yes	Yes	Yes	4	5	This plan Need set up in central of target object. Therefore, it is not suitable for one side wings connection.
Back	No	Yes	Yes	5	2	One type of general method. Which using for test force and frequency.

According to this table (5 is highest and 1 is lowest.), we can see that the centre support and one side support have a better average performance. Two side supports have high accuracy but are oversized. Because our project's main purpose is to focus on the force from the wing to the body, one side support would best fit our purpose, despite some potential influence from torque. To introduce this method, the wind tunnel will open a hole for a transition component. The force will go through this component to the force transducer, which should minimise the influence tunnel.

C. Limitation and design

The new design for this project includes a connection joint, which connects the wing and the sensor. More information can be found in the next figure. The connection joint can also increase the strain that helps the sensor read the force more easily from the wing. For the sensor system, there is a 4-strain gauge to set a one-dimensional sensor. The whole force sensor will constitute a 2-dimension sensor. In total, the force sensor includes eight strain gauges, two Wheatstone bridges, and two amplifiers. This system all together will include a force sensor and a connection joint.

Before beginning to design the hardware, some Geometrical constraint should be set on the design of the object. The first and simplest to consider is size, which is limited by the wind tunnel. The wind tunnel can be seen below in Figure X. The wing and shoulder joint will be set in a square measuring 220mm on one side. The wing length will easily fit, measuring between 120-180mm, including a 22mm length interface that connects with the wing and allows the force of the wing to transfer to the force sensor outside the wind tunnel.

A concept was devised to support the design requirements above. The diagram can be found in the appendix, including all of the equipment required.

Figure 4 shows where an attachment rod connects the target object and the force transducer. In this case, the force transducer should be two-dimensional, which requires two transducers. These hardware specifications were purposeful. The first intention was to reduce torque because the goal of this project is to test force, not torque. Load cells could be used to reduce torque efficiently. A precise design could reduce torque as well.

The signal transformation will follow Fig 4 as below.

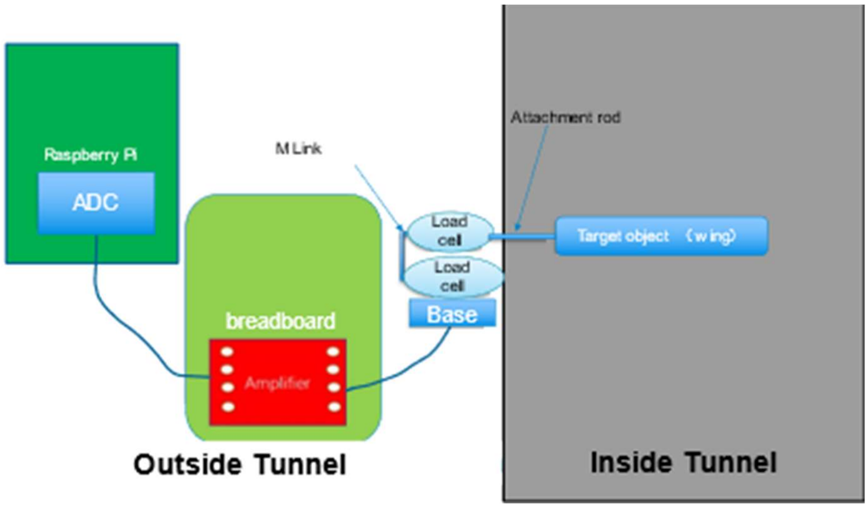

Figure 4 Connection Detail Sensor System

The force will pass through the wind tunnel to the force transducer, where it will be detected by the strain gauge force sensor and become an analog signal. After, the analog signal will be amplified and digitized by dedicated microprocessors. sent throughI2C. The data will be collected by an original program and analysed by MATLAB. Finally, the data processed by MATLAB will help researchers understand the force on target object. Transducers will connect to the amplifier of each dimension then connect to a data analysis software. The amplifier is a bridge between the load cell and ADC. After the amplifier, the signal will go to ADC. The signal noise probably will be generated from the load cell. To reduce the noise, a low pass filter will probably be required after the amplifier.

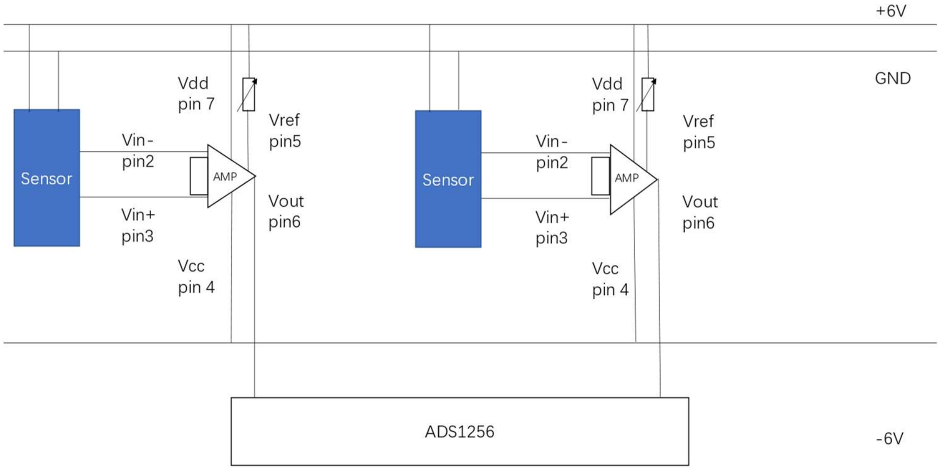

Figure 5 Circuit of sensor system

This circuit has a few requirements. The first is amplification. The noise from the sensor unit is incredibly low, which is around mV level lower than normal noise. The second is low signal noise. The signal noise is collected by breadboard, wire, and strain gauge. Third, due to this signal noise, a low pass filter in the circuit will be needed. Fourth, the ADC must be 24 bits, providing high resolution, but the total output voltage was between 0-5V. Because we chose raspberry pi as the final port, the maximum input voltage of raspberry pi is 5V.

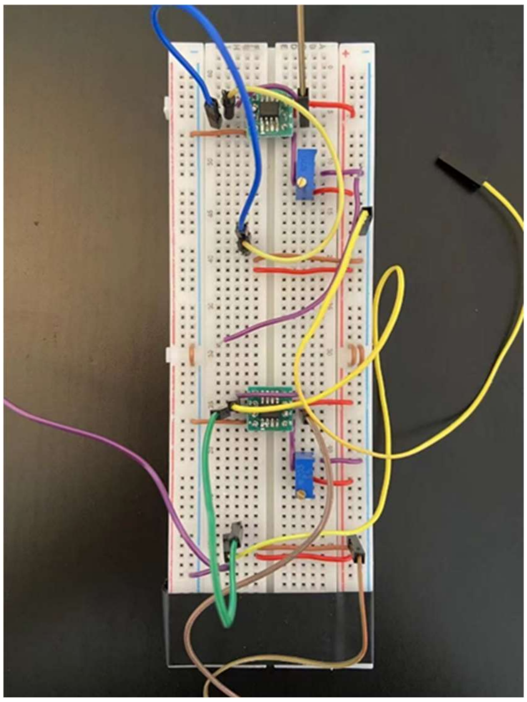

Figure 6. Amplifier Circuit

After considering size, the second limitation is sensitivity. According to Ştefănescu's article [12], the dragonfly force transducer should have a gram-force level resolution. Because this sensor is quite weak—only showing 5 mV compared to the human nervous system that shows 70 mV—this system will undoubtedly include some noise, which could not be cancelled. Therefore, a Kalman filter might work for this system instead. Several factors could influence the sensitivity: the strain gauge, load cell elastomer, Wheatstone bridge, or the amplifier. Some of these could be modified within these unstable parameters, such as the Wheatstone bridge and load cell elastomer. Some could not be modified, such as the strain gauge and amplifier, because these are productions. Therefore, precisely designing the load cell elastomer and Wheatstone bridge becomes the second important design requirement. To increase accuracy and resolution, it should include an amplifier, filter, and statistic function. The amplifier's work has been considered, which increases around 5mV to 3V.

The third limitation is Real-time detection, which means detecting wings change every millisecond. Real-time detection requires high-frequency data quality. This is a challenging program for the I2C port, and ADC performance. Most ADC only has an 80Hz sample data rate. Some ADC has high frequency, but when sample rates get too high, the data may lose accuracy. Therefore, it is hard to detect highly accurate data and high-frequency data at the same time.

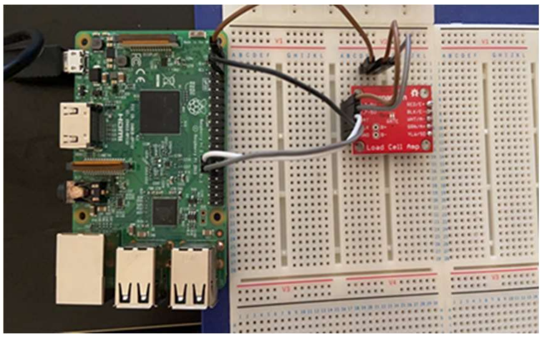

Fig 7. HX711 chip with Raspberry Pi

HX711 is a chip which design for reading data from load cell. The challenge with the HX711 chip was that it could only get a 10Hz sampling rate. So, the whole plan was redesigned using other devices. The device will be shown after.

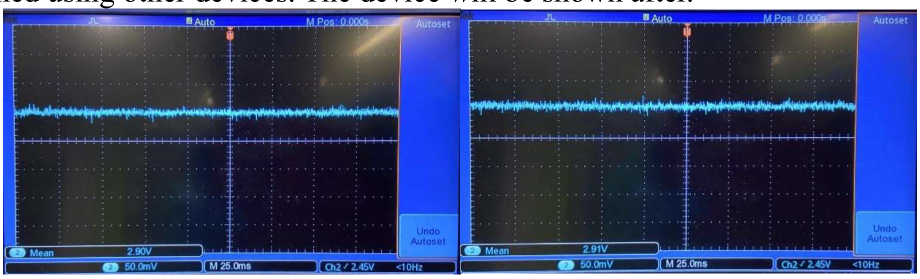

Fig 8. a) no LDF b) with LDF

Noise cancellation will be the fourth challenge in this project. The noise could be everywhere. For example, the wire, ADC, or even the sensors themselves will be collecting noise. Using an LDF (Low pass filter) is a way to reduce noise in the circuit. The LDF I designed for this circuit is designed to cut down signals with more than 3khz. The low pass filter did not work as well as theorised, though as shown in Figure 8, the LDF could not cut down noise from the entire system. Therefore, the LDF was removed because the noise may be less than 3khz.

The fifth challenge is to read a wide enough range of data. To achieve this, a slide rheostat was put on the reference pin of the instrument amplifier. For example, in some extreme conditions, the force may cause a high voltage, but the Raspberry Pi can only receive 0-5V. Changing the resistance could be a promising idea to detect higher-voltage data.

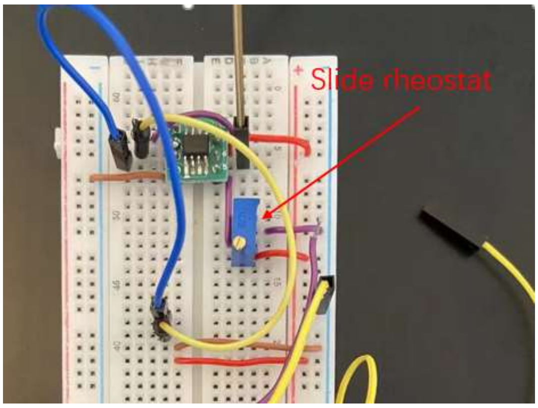

Fig 9 Slide Rheostat

Factoring in calibration and drift is the sixth and main problem with this sensor transducer. Improving accuracy and sensitivity will be difficult as well. Some alternate plans will also be tested in the experiment, such as changing Wheatstone bridges, using highly sensitive materials, and using mechanical methods. In the end, a software method was the best solution. Normalisation is necessary for every sensor system. The drift may come from anywhere, such as the load cell, amp, or ADC. Therefore, to prevent this, a normalised action at every start sensor system is necessary. The first idea is to use a sliding rheostat against drift, but that might take a long time. A program could handle this problem simply by taking stable data before the object takes any force.

The torque is the seventh challenge. There is a function in the program to address this problem, but the load cell is able to reduce torque. In some experiments, I give sensor units some torque and force, but only force could be detected. The voltage could cause a conversion of newton-force to gram-force by linear regression. The voltage is generated by the load cell and amplified by the amplifier. The load cell's one attribute is linear output, despite some errors.

There are many ways to consider recording and collecting data. Raspberry seems to be the most suitable force detection method for our project because there is no more space and budget to add a computer for the sensor system. There are many types of amplifiers, but operational amplifiers are the most popular and common type. However, the operation has limitations, such as high drift. Another possible amplifier is an instrument amplifier that can provide a low drift, and reverence voltage can help to calibrate quickly. So, in this project, an instrument amplifier becomes the first choice. Analogue-to-digital converters （ADC） have many parameters, such as limitations on how many bits can be accurately shown. Normally it is 8 – 16 bit, but some high accuracy ADC could be 24 bit or higher.

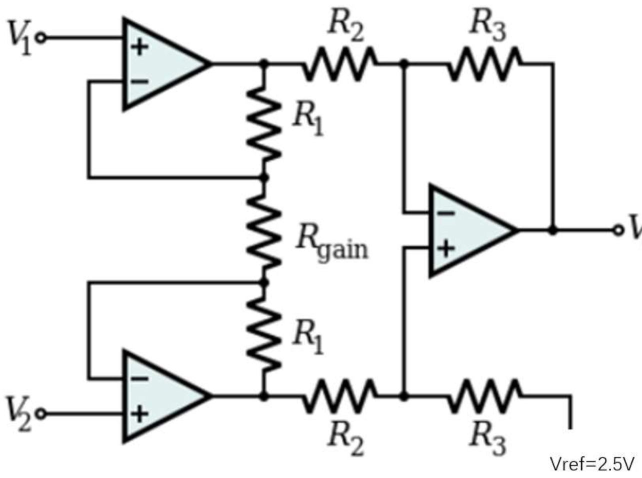

Fig 10 Instrument Amplifier sketch.

In addition, there is a test for test load cells working with crosstalk. The condition is used a hand to bending the end-effector meantime read data from the sensor, the result shows that will not affect another sensor.

4. Experiment design & Result

Motion capture is a system used to detect the position of the target object. To test if the complete system was working, we built a pendulum within the motion capture system. Using a periodic dynamic load that can be verified by a simple pendulum is an effective setup. When the pendulum's position changes, the force of the wire also changes. Therefore, according to the pendulum position, the force of wire could be simulated and detected by the force transducer system. The sensor system was tested by comparing the two different system's force charts.

I designed a simple pendulum experiment to test the accuracy of the proposed system. A 10.9-gram 3D printed weight was connected to the end of the effector with a low-stress string and five retroreflective markers were placed on the setup to capture the exact position of the pendulum using a motion capture system consisting of eight Miqus M3 cameras. 5 retroreflective markers were place on both the and effector and the pendulum to accurately track the position and state of the system at a mm level. The tracking data were been processed using MATLAB to generate simulated reference data.

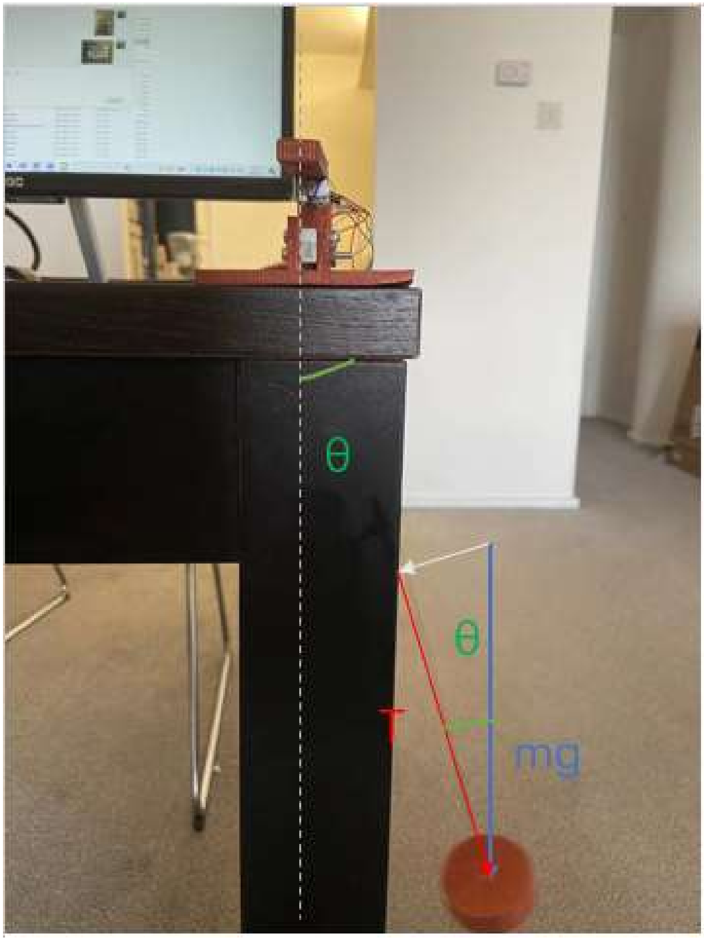

Figure 11 Experiment Equipment

According to Figure 11, the relationship between thread tension and gravity is clear. The tension force will be detected by the load cell in the yaw and pitch axis, by summing that up, using the swing angle θ, and pendulum weight *mg*, we can get the force of tension, therefore, simulate each axis force.

$$Mg\ cos\theta = T$$
$$T\ cos\theta = z\text{-}axis\ force$$
$$T\ sin\theta = x\text{-}axis\ force$$

According to the motion capture system, we would calculate the angle θ, from the equation above using θ could know the tension of wire and that connect to the end effector, So I can simulate the force of verticle and horizon.

I used TAL221 as a load cell [23], AD1256 [24] chip as the ADC, AD621 [25] / INA2126 [26] as amplifiers, and raspberry Pi for recording data. The program of ADC data reader has been updating many times, and the current program sampling rate is 2 KHz. There are many different reader programs in different languages.

The original data has some figures which are noise. To process the signal that comes from the ADC, a statistic function program is required. This function could get data from the ADC, minimise unreliable data and do a linear regression. The Kalman filter might be suitable for this target. The graph shown below explains that the Kalman filter is a good choice for reducing unreliable data.

5. Results

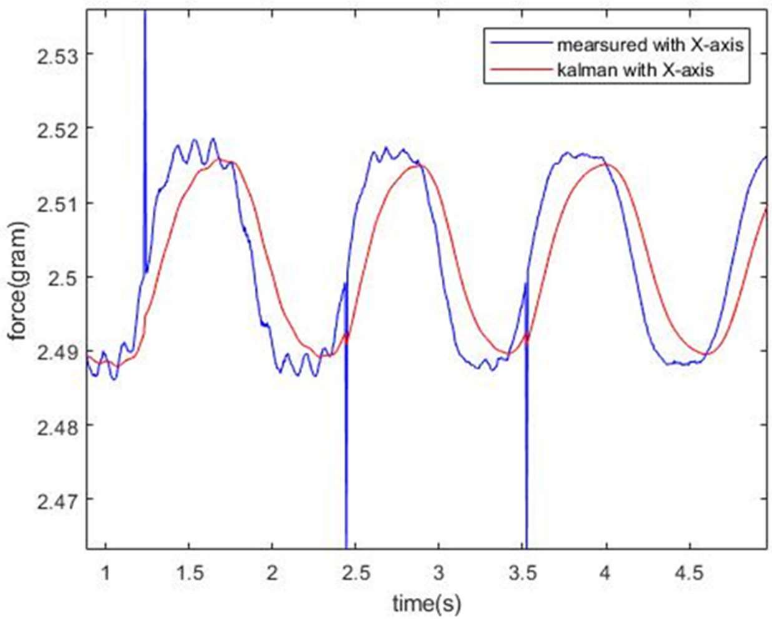

Fig 12. Original Sensor data & Kalman Sensor data

The red line shows after the Kalman filter has been applied, and the blue line shows original data. As shown above, the Kalman filter cancelled some unreliable data and reduced noise.

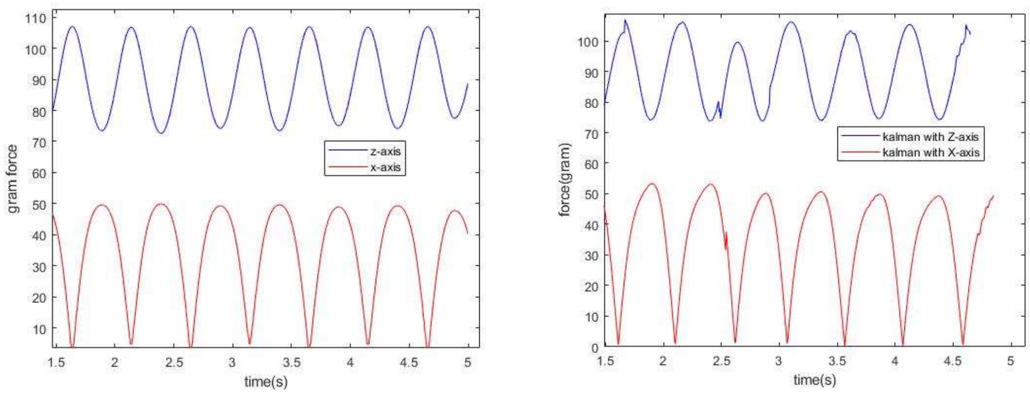

Figure 13 Simulation results vs Real data result (left is simulation and right are real data.)

The simulation result shows that when the pendulum swings, the force changes. The real data shows the same as simulation data, but there is still some data that is not smooth.

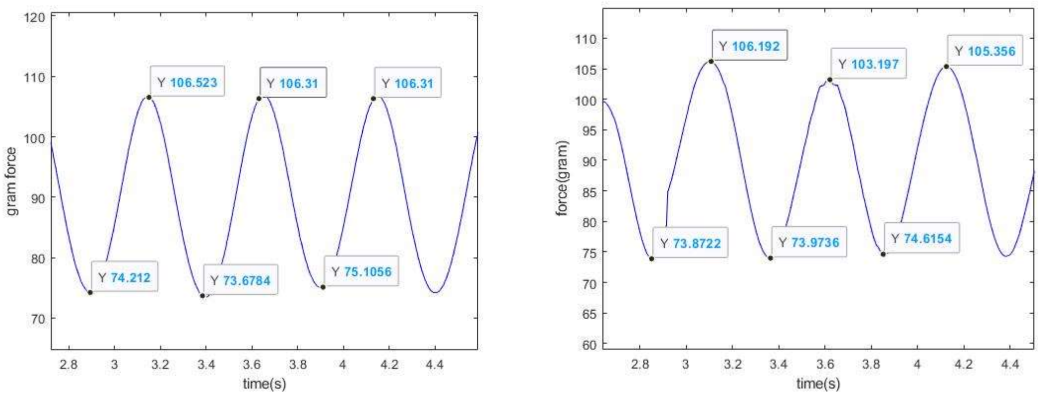

Fig 14. Z-axis (Vertical-axis) compering (left is simulation and right are real data.)

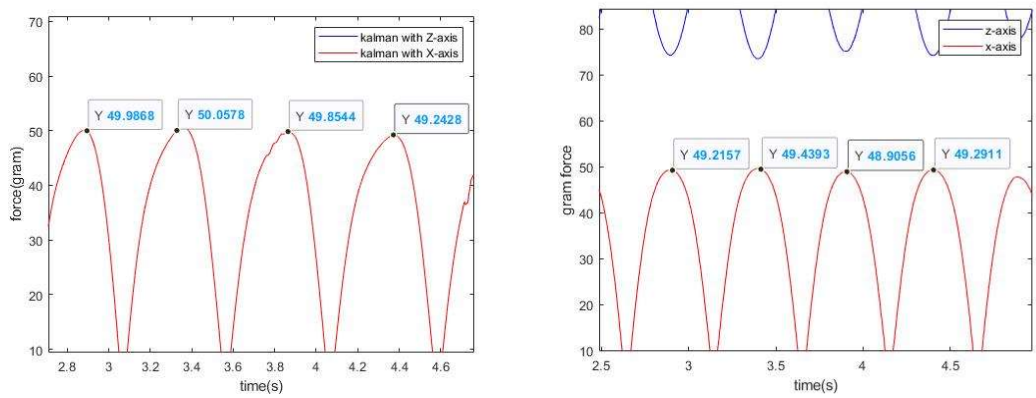

Fig 15. X-axis (horizon-axis) compering (left is simulation and right are real data.)

From the data, we can see the respect the Kalman filter makes the data smoother than before. There are some data that is still showing errors. On the other hand, simulation part also shows some unstable data. The real data is paring with simulation data from peak to peak.

I have tested two different instrument amplifiers in this experiment. The difference between the two amplifiers is that the higher one is 300 gains, and the lower one is 100 gains.

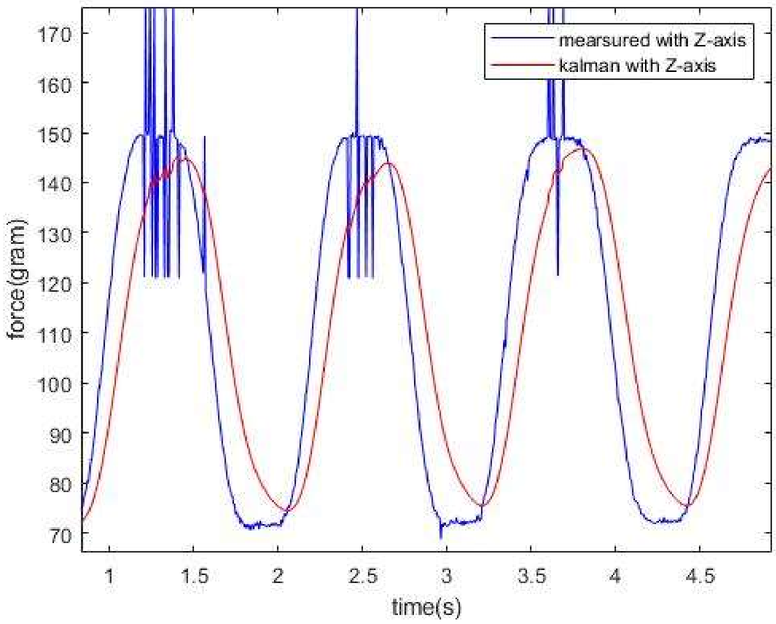

Fig 16 High gain AMP

The above figure shows a result with high gain Amp—the calibration function of the two amp is different. From the figure above, the Kalman filter is much smoother than the low amplifier.

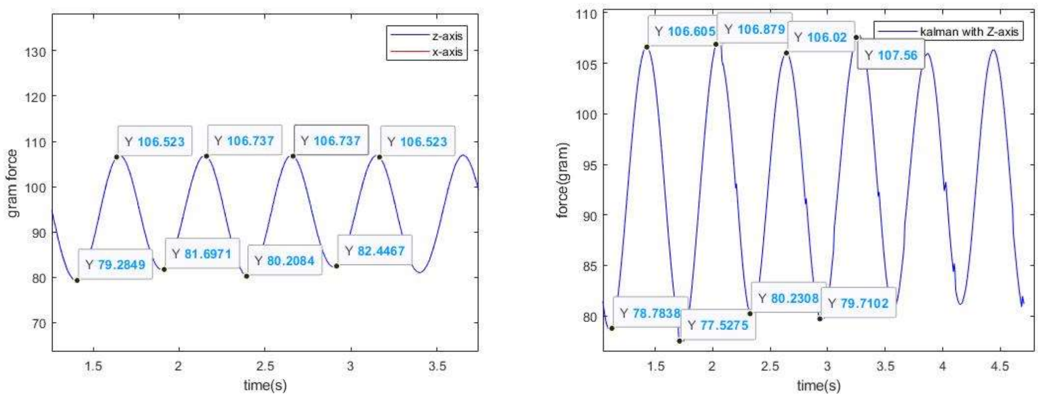

Fig 17. Z-axis (Vertical-axis) compering (left is simulation and right are real data.) with high gain AMP.

In the real experiment, high gain AMP shows high performance.

6. Discussion

Comparing the different sensors, the high gain did not provide high resolution because the Kalman filter and high solution of the ADC could read enough accurate data if it is well-calibrated. But high gain could help the Kalman filter to reduce the noise. The noise probably come from

ADC as the noise remains consistent after replacing the amlifiers, this can also be supported by the increase of peak error as the sampling rate increases. Therefore, the Kalman filter in this project is successful. This sensor system has been tested with a range of experiments, sampling data and demonstrating the system's ability to detect sensitive force (mN). This experiment cannot show the sensor systems' complete abilities because the accuracy of the simulation depends on the motion capture data, but the system's high performance was notable. There were some problems, however, which could not be ignored. Noise still affected the entire system, and the hardware was built with PLA materials, which showed deformations by the end of the experiment. There are many ways the accuracy of the system could be improved if these considerations were addressed.

7. Conclusion & Future plans

There are some parameters that may affect the final result. The PLA materials used to build this hardware took damage throughout the experiment. To counter this problem, the final version of the system's hardware should be constructed from alumina. The noise could be collected by breadboard or wire instead, making the final model completely protected by PCB (Printed circuit board). This system could accurately detect mN level force, therefore, it is not only suitable for wings but also other low-level force target objects. Furthermore, the system could be three dimensional or more, depending on the target object distance. If most of the target object is in the wind tunnel, only two dimensions of force are enough. Considering the objective and cost, this system is a high-cost performance solution.

8. References

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9. Annex(es)

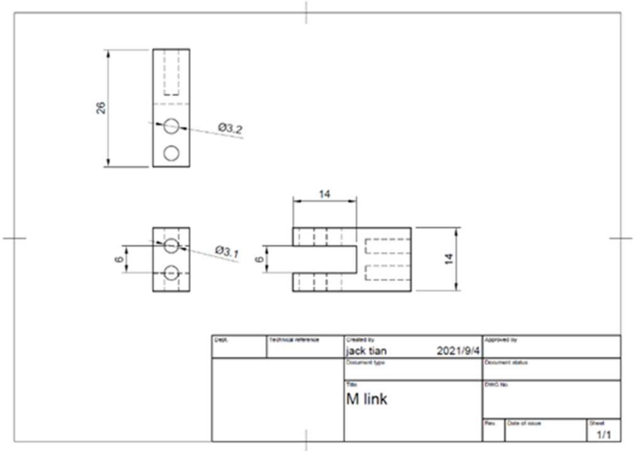


Figure 18 M Link

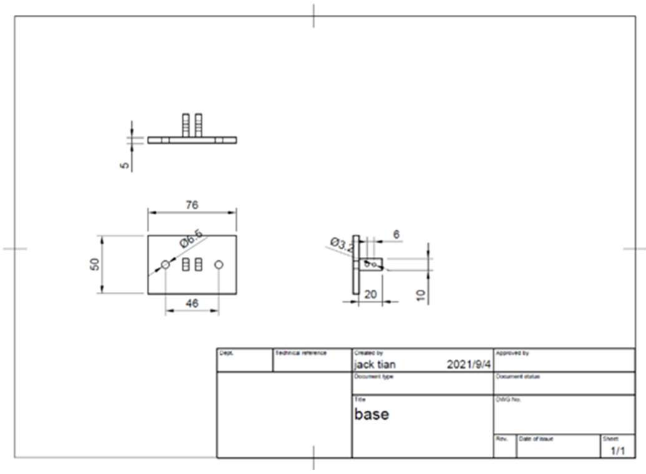


Figure 1 Base

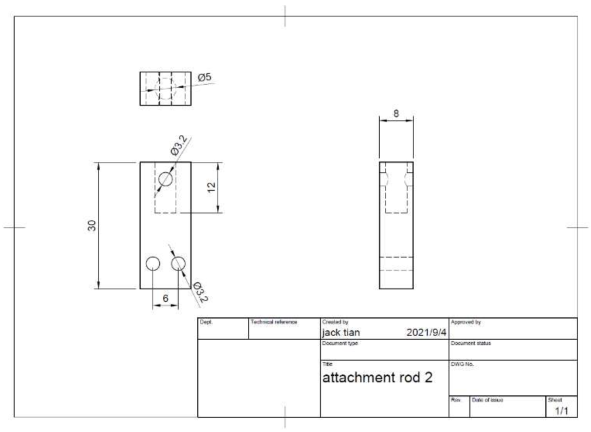


Figure 20 Attachment Rod

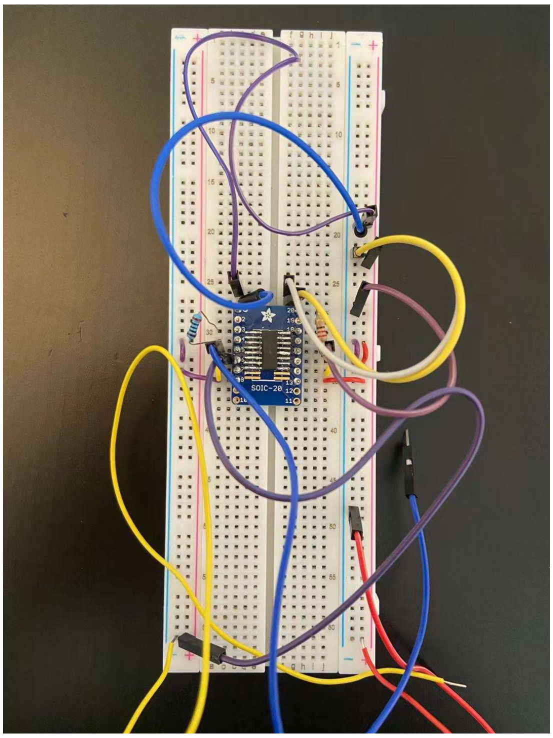
10. 

Figure 21 High gain AMP