EEE4113F Literature Review

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May 12, 2024

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Chapter 1

Introduction

> Philosophers have hitherto only interpreted the world in various ways; the point is to change it.
>
> —*Karl Marx*

1.1 Background

1.1.1 Problem Statment

Sally, a researcher at the FitzPatrick Institute, needs a way to weigh the red-winged starlings without startling them, because interestingly, they record their weight manually using a kitchen scale.

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3.1 Introduction

Weight is an important metric for evaluating the overall health, behavior and ecology of a bird in ornithological research. However obtaining this weight data presents several challenges due to their size, fragility and often rapid movements. This literature aims to explore and evaluate the different techniques and technologies researchers employ to obtain weight data, the different ways this data could be transmitted and recorded, and the types of devices needed to power such a system. This literature review will also consider the challenges described above and, other environmental and ethical factors that must be taken into account when weighing birds in the wild.

3.2 The Importance of Monitoring Avian Weight Changes

According to Clark, “Weight summarizes the total biomass of an individual and is probably the most convenient standard of energetic comparisons.” [2], which emphasizes how valuable the weight data of an individual bird can be. Baldwin and Kendeigh state that “The weight of birds and the variations and fluctuations of these weights furnish criteria of considerable importance in the understanding of the physiological and ecological reactions of the bird as a living organism [3], which further establishes how important the tracking of an individual bird’s weight data can be. Both of these statements cement how valuable weight data can be for ornithologists studying individual birds.

Clark goes on to say, “Weights have been used in analyses of the factors that influence differences in species diversity between communities.” [2]. They also state that “Weights and census data have often been combined to calculate the total biomass of a particular species or group of species in an area”. These statements add that weight data could also be invaluable for the analysis of an entire community of birds as opposed to just monitoring individuals.

3.3 Current Weighing Methods

This section examines the different methods and tools used to obtain weight data in ornithological research today.

3.3.1 Spring Scales

Spring scales measure weight based on the extension of a spring when a force (the weight of the bird) is applied. Their main advantage, as described by Manolis [4], is that they are "relatively inexpensive and sufficiently portable to suffice for short-term field project[s]". However, within the same study, the scale was only accurate to within 0,5g and when smaller birds can weigh less than 50g, spring scales may lack the precision for such research applications.

3.3.2 Electronic Scales

Electronic scales utilize load cells or strain gauges to convert the weight of the bird into an electronic signal, which can then be displayed on a digital screen. These scales offer precise measurements as shown by Carpenter et al. [5], where they were able to improve the precision of their measurements from 0,05g to 0,01g, by simply replacing their spring scales with electronic ones. Another advantage over spring scales, is that they do not have to be recalibrated after moving [5] and they tend to come with features such as taring functions to account for the weight of the housing holding the bird.

3.3.3 Perching Scales

Perching scales integrate a weighing platform into an artificial perch or nest. In Poole and Shoukimas' [6] study, birds landing on perch would deflect a transducer (a metal beam with 4 strain gauges bonded to it), thus generating an electronic signal. Reid et al. [7] used artificial nests rigged with a load cell in much the same way. In both studies, these electronic signals would then be recorded via some kind of electronic storage medium. This meant the birds could be weighed remotely, which minimizes stress and reduces the risk of injury, making perching scales particularly useful for long-term monitoring studies or behavioural observations. However, for such long-term studies, researchers would need to keep track of a large number of birds, which would also result in a large amount of data that needs to be stored.

Manolis [4] provides a solution to these issues by urging other researchers to make use of telemetry. One such technology is Radio Frequency Identification (RFID) which enables researchers to track individual birds and record their weight automatically. Wang et al. [8] made use of RFID by attaching two transponders to each bird, which would be detected by antennas placed under the perches. When a tagged bird interacts with the RFID reader, its unique identifier and weight are recorded electronically, making the data much easier to organise. It also reduces the volume of data created as the weight is only taken when the birds are on top of the perch. This allows researchers to collect data on a larger scale but this data need not be stored locally.

3.4 Data Transmission and User Interface

The method that the FitzPatrick Institute currently have for reading the bird weight is having one of the researchers go up to the scale and read off the screen. They then record the weight into *Cybertracker* [9], a mobile app that creates an Excel spreadsheet for them to analyze later. This highlights a need for a way to access that data remotely; or perhaps, a way to send that data directly to the Cybertracker app.

There are many communication protocols for transmitting data from a microprocessor. In a comparative performance study by Eridani et al., three protocols were compared: Bluetooth, Wi-Fi direct, and ESP-NOW ('a new protocol that allows multiple devices to communicate with each other without the use of Wi-Fi, with low power consumption' [1]). Five metrics were used in the tests: maximum range, transmission speed, latency, power usage, and signal resistance to obstructions [1]. A brief summary of the performance of each protocol is shown below in Figure 3.1.

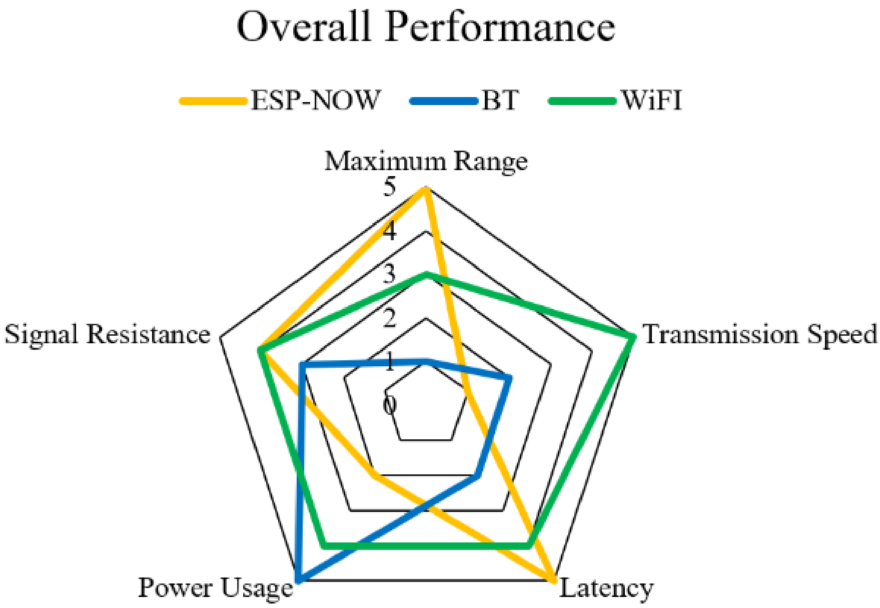

Figure 3.1: Overall Performance of each Protocol [1]

ESP-NOW performs best in range and latency; Bluetooth in power usage; and Wi-Fi in transmission speed. Since the scale must be portable, it is important to keep power usage to a minimum. A more quantitative graph of power usage of each technology is shown below in figure 3.2.

Figure 3.2: Power Usage Graph

Bluetooth has the best power efficiency and seems to provide sufficient range and speed. However, connecting the system to the user's phone requires effort on the user end, and perhaps expertise that the user may not have. In this case, connecting the system to the internet may be a better option (that is if an internet connection is available, i.e. if *eduroam* is in range).

Budoyo and Andriana used the internet when designing a prototype of a digital scale to measure the weight of onions. [10]. They interfaced the microcontroller (an ATMega2560) to the internet using an ESP8266 Wi-Fi module. The weight data is sent to a website where it is stored in a database. A database is useful in creating an Excel spreadsheet with many fields which is the end product that the client requires.

3.5 Power supply

Traditional weighing scales have relied on either battery or electric power sources for operation. Battery-powered scales utilize internal batteries, commonly alkaline or lithium-ion, to supply the necessary electrical power. This section will discuss the different types of power supplies available for bird scales and the power limitations on what type of power source the final design can use.

3.5.1 Wall Power

For indoor scales, which are in a fixed to one spot, the electric-type scales are directly connected to a power source via a cord, typically drawing from AC power provided by a wall outlet. These type of scales are used in laboratories and residential environments.

3.5.2 Energy Harvesting

One other method researchers use in low powered bird scales is Energy Harvesting. Energy Harvesting is used to extend the lifespan of the scale and sensing devices, however the process is not always effective [11]. An example of energy harvesting would be using wind or solar as a power source to the scale device. This concept is useful in situations where the scale is left in the field for data capture, and only accessed after a prolonged period of time. It is worth noting that low-power weighing scales are an existing topic, where in some cases there are scales and sensors that are able to take measurements, read and communicate the data in real time [12].

3.5.3 Limitations

The reliance on electrical power poses serious constraints, particularly in terms of mobility. This limitation becomes pronounced in specialized applications such as bird weighing scales, especially for very mobile birds such as the starlings. A better solution is to use a rechargeable battery source, such as the alkaline batteries mentioned above. Environmental conditions also pose a risk to the battery lifespan. Solar panels can pose collision risks for birds, particularly if the panels are highly reflective. Some birds may collide with solar panels while flying, leading to injury or mortality.

3.6 Challenges and Considerations

While modern weighing methods offer significant advantages in terms of accuracy, convenience, and animal welfare, researchers must consider several factors when selecting the most appropriate technique for their study.

3.6.1 Size and Species

The size and behaviour of the target bird species may influence the suitability of different weighing methods. Some birds may become skittish around researchers which would make measurements unreliable. In Manolis' case [4], they had to use binoculars to take readings of the scale from afar; an inconvenience that is entirely removed from the solutions presented by Poole and Shoukimas [6] and Reid et al. [7]. Smaller birds may require scales with higher precision, while larger species may benefit from perching scale systems capable of handling multiple subjects simultaneously.

3.6.2 Environmental Conditions

Field studies often expose equipment to challenging environmental conditions. For example, Manolis [4] had to keep swaying to a minimum to get accurate readings, hence spring scales would not be suitable in windy conditions. Rain can seriously damage electronic components so it was important for Reid et al. [7] to house the amplifier unit in "a small water-resistant case with a sealed connection to the data logger cable". Researchers must choose weighing methods that are robust and reliable under these circumstances, with weather-resistant features where necessary.

3.6.3 Material Considerations

An important consideration that our design would need to fulfill is that it is safe for use on birds. Given that they will be in direct contact with the scale, toxicity is a primary concern when considering the materials used to construct the scale.

In the design of an electronic scale, artificial materials such as plastics are an attractive option due to their naturally weatherproof properties. However, caution must be exercised when considering specific materials. Artificial materials such as polytetrafluoroethylene (PTFE) are a common source for airborne toxicity in avians [13]. However, in a paper by Kroshefsky [14] this material is only cause for toxicity concern when exposed under high temperatures. This is because PTFE begins to decompose in air at around 200°C. Even if the scale is place outdoors, the ambient temperature will be well under this temperature limit, making this material a viable choice in the housing.

Heavy metal poisoning is another important concern when it comes to our choice of materials. The most common occurrences of which come from the ingestion of lead [15]. When lead is ingested, it can be absorbed in the gastrointestinal tract and then taken up by soft tissues and eventually bone [15]. The paper by C. Pollock includes a list of common sources of lead in household items, the most notable of which is solder. Thus some kind of insulation is required around soldered circuitry to avoid any trace amounts of lead affecting the birds.

3.6.4 Ethical Considerations

Ethical guidelines emphasize the importance of minimizing stress and harm to the animals being studied. As such researchers should prioritize methods that avoid the need to handle the birds, as this will minimize the risk of injury to the researchers and the birds. This means that the red-winged starlings will need to be lured such that their weight measurements can be taken. This can be achieved using the many perching scale solutions described earlier, but for more traditional weighing methods, Manolis [7] provides a solution. In their study they used sunflower seeds to entice the birds to land on the scale, and since red-winged starlings tend to scavenge for food, this will prove useful for this application as well.

An automatic feeder device could be implemented as a way to streamline this process. However, researchers have found that the introduction of automated feeders tend to reduce species variety in a given area [16]. Automated feeders are also highly inconsistent with seasonal change, which would result in it being a highly inconsistent form of luring birds [16]. The introduction of an automated feeding strategy would have a noticeable effect on the ecological and weight cycles of local birds, especially those that would be studied.

3.7 Conclusion

Based on the reviewed literature, it can be seen that accessing data remotely is very much feasible using accessible technology such as Wi-Fi. The importance of gathering weight data was established and how it would be of benefit to ornithologists was explored. Various challenges and considerations have been presented in the reviewed literature and the importance thereof will be taken into account going forward.

Chapter 4

Sensing Subsystem (NXSMPI001)

4.1 Introduction

The aim of this subsystem is to translate the force from the bird's weight on the scale into a digital reading. It involves designing and constructing the circuitry needed to change the weight into a analogue voltage, developing the algorithms in the micro-controller unit (MCU) used to process this signal and change it into a weight reading of the bird. Another component to this subsystem is to have accurate timekeeping so the weight data is timestamped.

4.2 Requirements Analysis

Table 4.1: Non-functional Specifications of the Sensing Subsystem

User Requirement	**Specification Description**	**Specification no.**
Portable	The final circuitry must be able to fit in a box that is 100x100x50mm.	SS1
Long battery life	The final circuitry should consume less than 30mA.	SS2

4.3 Design Process

4.3.1 Microcontroller Unit (MCU)

The Arduino was chosen as its Integrated Development Environment (IDE) has ample support and libraries which will make interfacing with all different modules simple and straightforward. Within the Arduino family the Arduino Nano was initially chosen as it was one of the cheapest Arduino and it came in a small form factor. However, the User Interface subsystem required a WiFi or Bluetooth module so the Arduino Nano 33 IoT was chosen instead. Although BLE and BLE Sense also meet these requirements, they come with additional sensors that are unnecessary. All the Arduino chips also come with several low power modes that can be leveraged to reduce power consumption.

4.3.2 Weight Sensor

A strain gauge is an electrical component whose resistance changes when a force is applied to it. Strain gauges work on the principle that when the resistance of a conductor is proportional to its length, as

Table 4.2: Functional Specifications for Sensing Subsystem

User Requirement	Specification Description	Specification no.
The scale must measure weights of up to 500g.	The weight sensor must have a maximum capacity greater than 750g (1.5 times safety factor).	SS3
	The sensor and amplifier must output a voltage proportional to the weight force applied up to a weight of 500g.	SS4
	Microcontroller must have an algorithm for converting output codes from the ADC into a weight measurement.	SS5
The scale measure weight accurate to 0.1g.	The ADC must be able to resolve voltage changes from weight changes that are less than 0.1g.	SS6
	The ADC must have a gain and offset error less than a voltage change resulting from a change in weight of 0.1g.	SS7
The scale must have a tare function to ignore the weight of the perch	The microcontroller must have a digital input pin to read the user's inputs.	SS8
	The microcontroller must subtract the current weight from all subsequent measurements when the digital pin receives an input.	SS9
	There must be an LED that indicates when the scale is in tare mode.	SS10
The scale must be battery powered.	The microcontroller and all the surrounding circuitry must be able to operate with one positive rail.	SS11

shown in the equation below.

$$R = \rho \frac{L}{A}$$

One solution is to put a strain gauge in series with another resistance, then place the strain gauge on a beam. When the beam deflects under the bird's weight, the change in voltage across the strain gauge can be measured. The issue with this setup is that the change in resistance, and thus the subsequent change in voltage, will be very small. This means a very high resolution ADC will be required to resolve these small changes in voltage. The resolution required could be reduced by amplifying the signal, however this would also amplify the DC offset introduced by the voltage divider, quickly saturating the output.

A better solution is a load cell which has 4 strain gauges in a Wheatstone configuration. This means that when the load cell has no load on it, the voltage will be zero, and when the device deflects, there will be a slight voltage difference between it's 2 output terminals. As discussed above, this output can be sent through an amplifier thus reducing the resolution required for the ADC. To meet the sensor specifications, a 1kg load cell will be used.

The specifications for one such load cell by HKD is shown in Table 4.3 below.

Table 4.3: Table on load cell specifications

Rated Load	1kg
Rated Output	1.0 ± 0.15mV/V
Zero Output	±0.1mV/V
Input Impedance	$1115 \pm 10\Omega$
Output Impedance	$1000 \pm 10\Omega$

At the rated load, the output will be $0.001V_{cc}$, hence the amplifier needs a gain of 1000.

4.3.3 Sensor Amplifier

From Table 4.3, the output impedance of the load cell is quite significant, meaning there will need to be an input buffer between it and the amplifier to avoid loading. The instrumentation amplifier is thus ideal circuit for achieving this and it is shown in Figure 4.1 below.

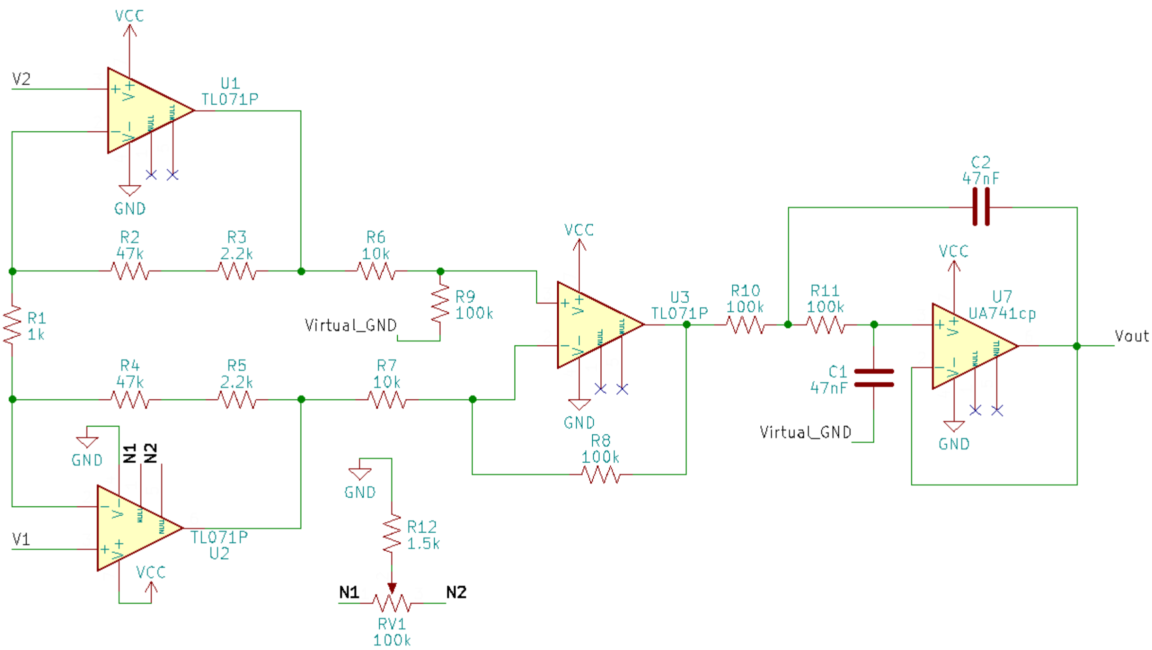

Figure 4.1: Circuit Schematic of Instrumentation Amplifier

The circuit has three stages. The first stage has two input buffers which also amplify the input signal. The second is a differential amplifier which is a circuit whose output is proportional to the difference between the two inputs. The final stage is a low pass filter. The final output voltage is related to the input voltage by the expression below.

$$V_{out} = (V_2 - V_1)\left(1 + \frac{2(R_2 + R_3)}{R_1}\right)\left(\frac{R_9}{R_6}\right)$$

From the expression above, when the load cell is connected to the two input terminals, its output will be amplified by a factor of 994, which is close to the gain required. The amplifier have such a large gain presents two issues.

The first is that real op-amps have an input offset voltage. As the offsets from the input stage propagate through the circuit, they are amplified resulting in the output having a large bias and saturating for very small weights, hence the op-amps used were the TL071P. These are JFET op-amps meaning they have a very low input offset voltage, in this case, of 1mV. This is still large in comparison to the input, but they also come with two NULL pins which allows the input offset to be adjusted, and thus reduced to 0. The is the purpose of potentiometer RV1 in Figure 4.1. Another reason for choosing TL071P is that their minimum recommended supply voltage is 4.5V which means unlike other JFET op-amps they can operate at lower supply voltages. This advantageous since the scale will be battery powered so there will not be a large supply.

The second is that noise from the input will also be amplified as it propagates through circuit, making the final output difficult to measure. The low pass filter in the final stage addresses this. Since output is a DC voltage, ideally the cutoff frequency should be as low as possible to attenuate the most amount of noise, but this would have a negative impact on the rise time. A lower cutoff frequency would also require larger capacitors. The sample rate for final system will be 10Hz (discussed later). This equates to a period of 0.1s and ideally the output should settle within half that time. It takes 5 time constants for the output to settle to 99% of its final value. This means that $5RC = 0.05s$ or $RC = 0.01s$. If a 100kΩ resistor is used then the capacitor would need 100nF. The filter also needs a steep roll-off to ensure a clean output, so a second stage can be added at the input, to make it a second order filter. The input stage of this filter needs to have much lower impedance than output stage to avoid loading, which would resulting in the filter having a larger cutoff frequency than was calculated. Using a 10kΩ resistor, the capacitor needed would be 1uF. The equates to a cutoff frequency of 16Hz. It is difficult to know the exact rise time for higher order filters from calculation alone, as such, this filter was simulated in LTSpice. The circuit diagram is shown in Figure 4.2 below.

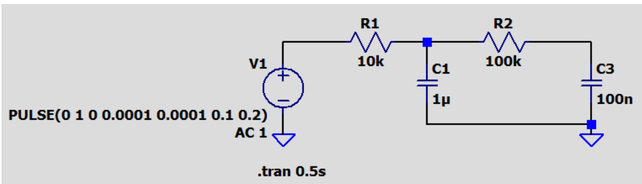

Figure 4.2: Circuit Schematic of Low Pass Filter

The input was set to a $1V_{pp}$ square wave with a frequency of 5Hz. Figure 4.3 below shows the input and output of the circuit.

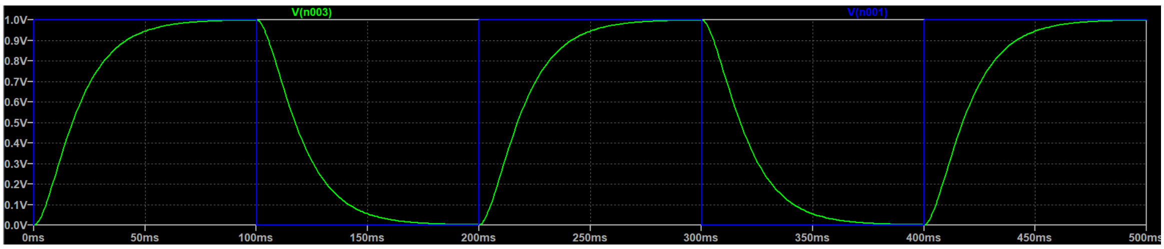

Figure 4.3: Input and Output Waveform of Filter

From the waveform above it can be seen that the rise time is too large, as the output (in green) is barely settling in time for the next half-cycle. This can be rectified by halving the size of the capacitors to 470nF and 47nF, as seen in Figure 4.1. The new output is shown in Figure 4.4 below.

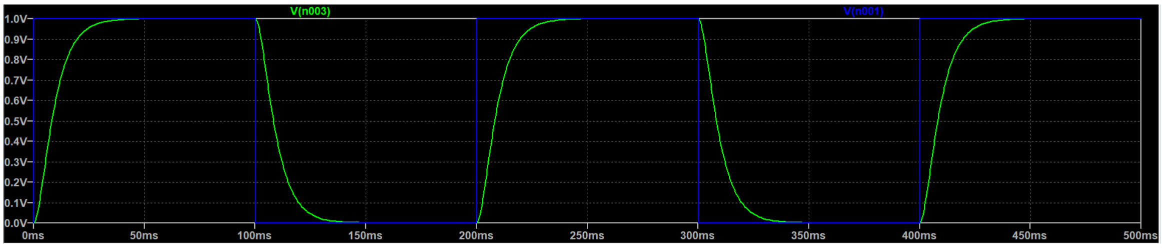

Figure 4.4: Input and Output Waveform of the Final Filter

As seen above, the filter now meets the speed requirements.

Since the instrumentation amplifier has op-amps, it needs 2 rail voltages, a positive and a negative. Unfortunately there is only a single supply, however this supply can be split in two with a simple op-amp circuit, as shown in Figure 4.5 below.

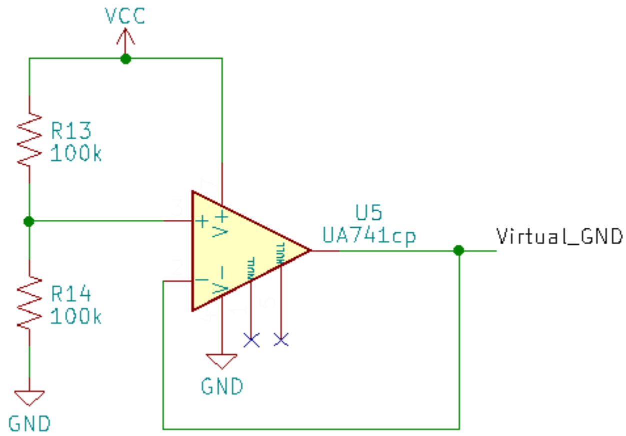

Figure 4.5: Schematic of Split Supply Circuit

If the new reference point is made to be 'Virtual GND', then two rail voltages equal to $\pm\frac{V_{cc}}{2}$ are obtained. This does mean that output of the amplifier will have an offset of $\frac{V_{cc}}{2}$, but this can be stepped down using a voltage divider as to not damage the input to the microcontroller. In testing, a 5V supply was initially used but this resulted in the op-amps saturating. In the early stages of the design process, the amplifier was tested using $\pm 3.3V$ and this worked fine so in the end a 6.6V supply was chosen. This will be the supply voltage required from the Power Subsystem. The Arduino Nano 33 IoT has an operating voltage of 3.3V so the voltage divider must have a gain of 0.5.

Finally, because the output from the amplifier will no longer go directly to the microcontroller, an op-amp must be included in the low pass filter to buffer the input of the voltage divider. The new active low pass filter will be in a Sallen-Key configuration with $R = 100k\Omega$ and $C = 47nF$ as shown in Figure 4.1.

4.3.4 Analogue to Digital Converter (ADC)

Since the weight force on the load cell is proportional to output voltage out of the load cell, the change in weight is equal to the change voltage as shown in the equation below.

$$\frac{W_1}{W_2} = \frac{V_1}{V_2}$$

By substituting in the rated load, rated output and the minimum weight, the smallest change in the output can be determined.

$$\frac{0.1g}{1000g} = \frac{V_{min}}{0.5(994(3.3mV))}$$
$$V_{min} = 0.164mV$$

As such, 1 LSB (Least Significant Bit) of ADC must be less than 0.164mV. Since the supply voltage from the Arduino is 3.3V, an ADC with a minimum resolution of 15 bits is required. The Arduino only comes with a 12-bit ADC so an external module will be needed. The module that was chosen is the ADS1115 16 bit ADC its specification for this application are summarized in Table 4.4 below.

Table 4.4: Table on ADS1115 specifications

	Min	**Typical**	**Max**	**Unit**
Supply Voltage	2	-	5.5	V
Data Rate	8	-	860	SPS
Offset error	-	± 3	-	LSB
Gain error	-	0.01	0.15	%

From Table 4.4, the offset error is equivalent to 0.151mV which is less than V_{min}. The maximum gain error is quite large, translating to an offset of 4.95mV at the last output code. Even under typical conditions the offset will be 0.33mV. However this is not a big issue, as the scale only needs to be accurate over half the range and the gain error can be compensated for in software. The noise performance is also great as at low data rates, not a single bit of resolution is lost to quantization noise. The final reason this module was chosen is that most ADC come standalone in a SIOC package, but this one comes as a development board kit with headers allowing for easy soldering onto a Veroboard. The circuit diagram for this module is shown in Figure 4.6 below. The ADC communicates with

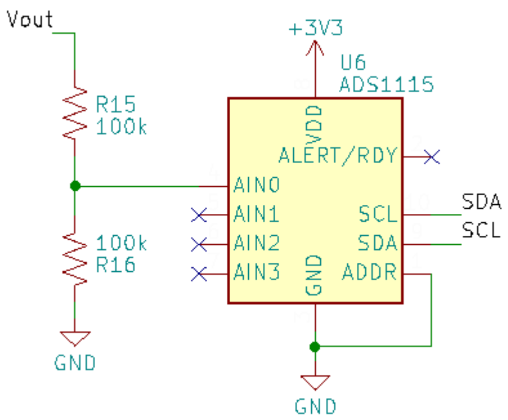

Figure 4.6: Circuit Schematic of the ADS1115

Arduino the I2C communication protocol, hence their SDA and SCL lines are connected. The Arduino has internal pull-up resistors on these lines so there's no need for external ones. The output from the amplifier is halved by the voltage divider and sent to channel 0 on the ADC. This is necessary as the ADC can only take 0.3V above the supply. In this case the supply will be the regulated 3.3V from the

Arduino.

4.3.5 Weight Measurement Algorithm

The ADC was read from in code using the ADS1X15 Arduino library by Rob Tillaart [17]. The ADS1115 has a programmable gain amplifier (PGA) that allows it take more precise measurements at the cost of a reduced input voltage range. The different options for the gain with corresponding full scale range and precision are shown in 4.5 below. The second option for the gain was chosen

Table 4.5: Table on ADS1115 gain options

FSR [V]	**LSB Size [uV]**
+/- 6.144	187.5
+/- 4.096	125
+/- 2.048	62.5
+/- 1.024	31.25
+/- 0.512	15.625
+/- 0.256	7.8125

since the input is expected to be between 1.65V and 3.3V. The LSB size for this gain also meets the accuracy requirements. The data rate was also set to 16 samples per second as the sample rate for the system will 10 samples per second. These were both set in code using the setGain() and setDataRate() functions from the library. Once setup, the sampled value would be read from the ADC using the readADC() function. The ADC value was then converted into voltage in Volts by multiplying by the value returned by the toVoltage() function. That voltage is then converted to a weight in grams using the function shown in Figure 4.7 below.

```
float voltsToGrams(float V) {
  float Vin = (2*V -3.3)/994;           // Determine input voltage from output voltage
  float weight = 1000*Vin/(3.3*0.001);  // Determine weight from input voltage
//  float weight = (V-1.5935)/0.0015;   // Linear regression model
  return weight;
}
```

Figure 4.7: Code Snippet of the Function that converts voltage to a weight

The output voltage from the amplifier is given by the expression below.

$$V_{out} = \frac{1}{2}(994V_{in} + 3.3)$$

The input voltage from the load cell is found from the output voltage using the expression above. The weight is then determined from the input voltage using the fact that they are proportional, and this was implemented in code as shown in 4.7 above.

The final outputted weight value was the ten-point moving average of the all the measurements. The function shown in Figure 4.8 implements this algorithm in code. If 'SIZE' is set to 10, the values array is a circular buffer that stores last 10 weight measurements, along with the sum of the whole array. The index increases incrementally with each new measurement and wraps back around to 0 once it

```
float movingAverage(float* values, int index)
{
  float sum = values[SIZE];
  sum += values[index];
  if(index+1<SIZE) {
    sum -= values[index+1];
  }
  else {
    sum -= values[0];
  }
  values[SIZE] = sum;
  return sum/SIZE;
}
```

Figure 4.8: Code Snippet of the Function that takes the Moving Average of the weights

goes past 9. This means the latest value is stored at position 'index' within the array, while the value one position ahead is the oldest. When a new value is added to the array, it is added to the sum while the oldest value is removed from the sum. The sum divided by 10 is then average that gets returned. By storing the sum in memory it removes the need for adding up all the values in the array when every measurement, making the program run more efficiently.

4.3.6 Tare Functionality

The tare function was implemented using an interrupt tied to a push button. When the button is pressed the LED is toggled, and the current weight is stored is added to an offset value. The resulting measurement will be the difference between the weight and this offset, unless the offset is larger, in which it is just 0. This was implemented in code as shown in Figure 4.9 below. When a button is

```
void buttonPressedISR()
{
  if(millis() - last_press > DEBOUNCE_DELAY){     // Button debouncing
    digitalWrite(LED_PIN, !digitalRead(LED_PIN)); // Toggle LED
    last_press = millis();
  }
}
```

Figure 4.9: Code Snippet of Interrupt Service Routine for push button

pressed it bounces open and close many times in a split second, resulting in the microcontroller reading multiple inputs from one button press. Hence a delay of 250ms is added to allow the button to settle before taking input from it again.

4.4 Acceptance Test Procedure (ATP)

4.4.1 Load Cell and Amplifier tests

The amplifier circuit built on the breadboard and connected to a 6.6V power supply. The split supply was tested by measuring the voltage of the positive and negative rail with respect to 'Virtual GND' using a multimeter as shown in Figure A.1 in Appendix A4. The input into the amplifier was connected to the waveform generator on the oscilloscope. The output with respect to 'Virtual GND' was measured using the oscilloscope and the output with respect to GND was measured using the multimeter (this is what the ADC would measure). The input was set to 0V DC and the potentiometer was adjusted until the measured output on the oscilloscope was also 0. The output to the Arduino was then measured using a multimeter. This was repeated for different input values until the output saturated. This was compared to the ideal output given by the following expression.

$$V_{out} = \frac{1}{2}\left(994V_{in} + 3.3\right)$$

The measurement for the output when the input was 1mV DC can be seen in Figure A.2 in Appendix A4.

The load cell was attached to a mock scale as shown in Figure 4.10 below. Header pins were soldered to each of leads from the load cell. Within the same figure, the red and black leads were connected to V_{cc} and $Virtual\_GND$ respectively, while the white and green wires leads connected to the V_1 and V_2 inputs of the amplifier respectively. A kitchen scale was then used to measure and record the weight of an empty water bottle. This bottle was then placed on the front of the scale above the nails. The output voltage from the amplifier was measured and recorded the same as before. This is shown in Figure below. This process was repeated for different weights up until the amplifier's output saturated. The weight of the bottle was varied by filling it up with different amounts of water. The bottle was placed at the same position on the scale in each run to ensure that the bottle's distance from the other end, or moment arm, was the same.

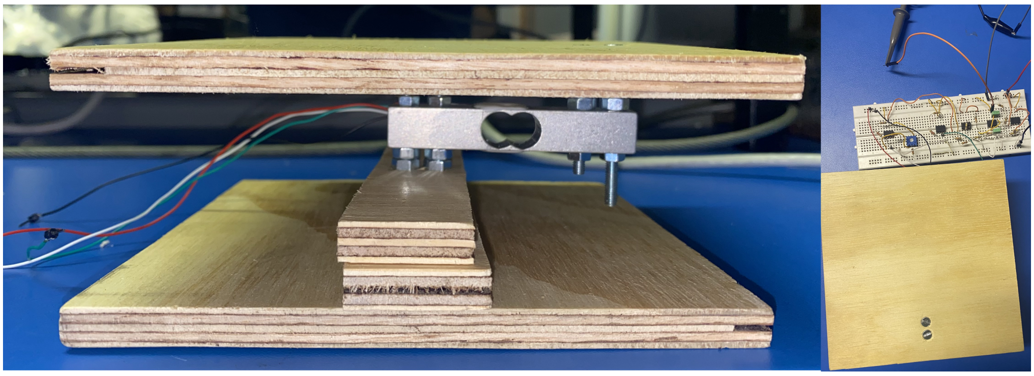

Figure 4.10: Image of mock scale

4.4.2 Weight Measurement Test

The ADC was connected to the Arduino as shown in Figure 4.6 on the breadboard. The output from the voltage divider in Figure 4.10 was connected to channel 0 on the ADC. The Arduino was connected to the PC, the weight measurement program was run and a serial connection was established to see the output in the terminal. Once again, a bottle filled with different amounts water was placed on top of the load cell. The weight of the bottle measured by the scale and the weight measurement determined in code were both recorded. The measurement for the empty 66g bottle is shown in Figure A.1 below.

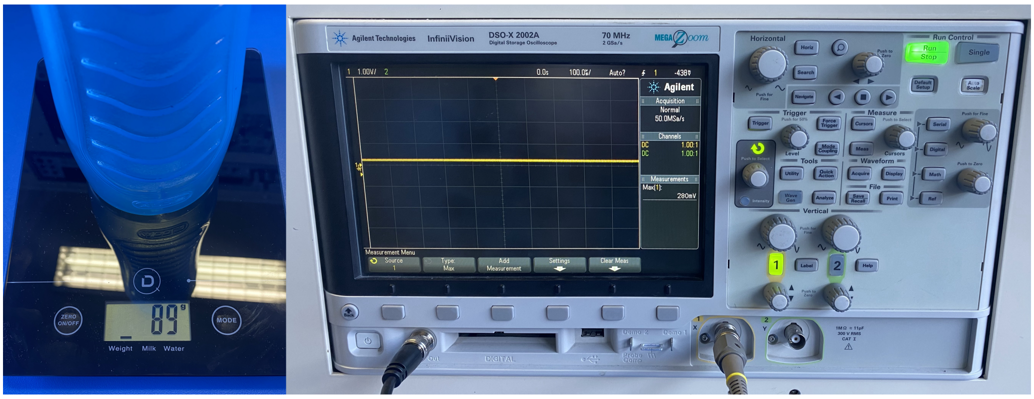

Figure 4.11: Image of load cell and amplifier test

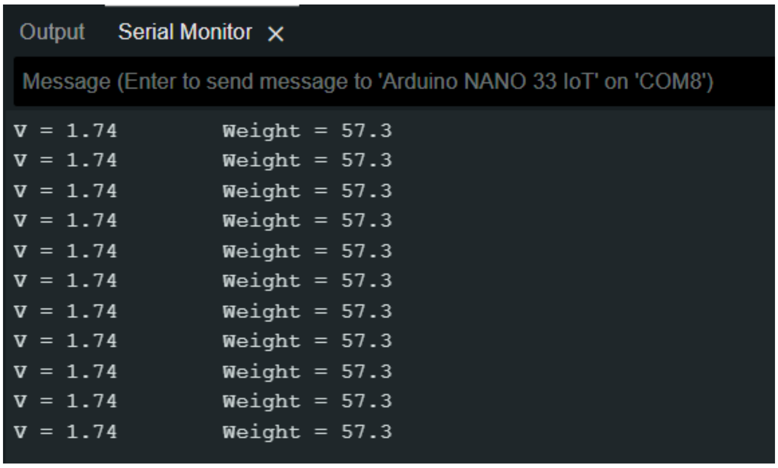

Figure 4.12: Image of Weight measurement in terminal

4.4.3 Tare Function Test

The push button was now connected to pin

4.5 Results and Discussion

4.5.1 Load Cell and Amplifier test

The plot of the output voltage w.r.t. GND and 'Virtual GND' against the input voltage from the oscilloscope can be found in Figure A.3 in Appendix A4. The plot of the output voltage against the weight is shown in Figure 4.13 below. It can be seen that the output voltage has linear response with the weight.

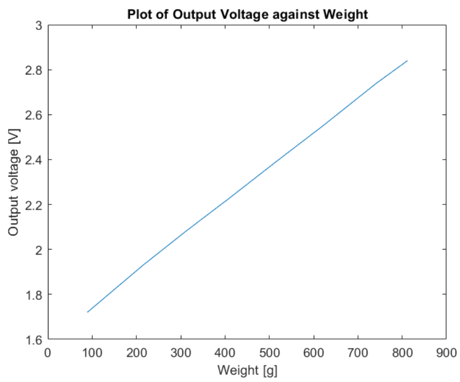

Figure 4.13: Plot of the output voltage against the weight

limiting

Chapter 5

Power Subsystem (MBSLUN008)

5.1 Introduction

The power subsystem is one of the most important subsystems in the design with respect to its functionality. This subsystem is responsible for powering up the micro-controller (MCU). It is very important for the design to have a reliable and safe power supply unit (PSU). This section outlines how the power supply unit design is divided into smaller sections, all with different responsibilities, requirements and specifications, but with the same goal: to achieve a reliable power supply source. The design uses a battery as its primary source of power. The subsection includes sections such as battery charging, overload protection, reverse polarity and a voltage regulation system. Designed were two circuits which work together to complete the whole PSU. First circuit is for battery charging, encapsulated with protection, then the voltage regulation circuit. As abovementioned, the PSU's goal is to provide a reliable power source to the micro-controller for more efficient performance.

5.1.1 System overview

Shown below is the system overview of the whole power supply unit.

5.2 User requirements

5.3 Specifications

5.4 Design

5.4.1 Battery charging

Lithium-ion batteries are rechargeable, The charging circuit should have a stable power supply. This supply can be achieved by using a wall adapter, USB port, or another power source, such as a power bank. The charging circuit of the 18650 Li-ion batteries uses a BC745 PNP transistor as the driver of the circuit. The circuit diagram is shown below. The circuit takes in a voltage of between 8V - 5V. This circuit is designed to charge one battery at a time, making it more efficient and reliable. The charging circuit has two LED indicators. These LEDs are designed to indicate the level of the battery power when it is plugged to the charger. When the voltage is low, i.e the battery power is low, the RED LED will be much brighter than the GREEN LED. When the voltage now approaches the maximum voltage of 4.2V (actual voltage on a 3.7V Li-ion battery), the green LED dominates the RED and the user can know that the battery is charged. This is a sample and cost effective way to monitor the charging process of the batteries.

5.4.2 Battery Protection

Overload protection

During the charging process, the 18650 battery must be protected against voltage and current overloading. The overload protection should keep note of key considerations and address to ensure both safety and optimal battery performance. The Li-ion battery has a nominal voltage of 3.7V, it is imperative to note that the specifications of the battery state that the charging voltage should not exceed 4.2V at 0.052A. A common approach involves incorporating a dedicated protection IC that monitors charging parameters such as voltage, current, and temperature. When an overload condition is detected, typically caused by excessive current flow or prolonged charging beyond safe limits, the protection IC triggers a mechanism to shutdown and disconnect the charging circuit from the battery. This prevents overcharging, which can lead to overheating, cell damage, or even fire hazards.

In the circuit below, a 10k ohms variable resistor was used to vary the voltage of the circuit. Resistors to the values shown below are used to limit the current in the circuit. A power transistor LM395 is used in the overload protection as shown. LM395 is ideal for low power applications such as our small scale sensing design. These transistors act as high gain power transistors, and are capable of power, voltage, current limiting and heat/thermal overloading protection. It is very rare to find a device which is able to provide overload and thermal protection concurrently, which makes the LM395 very reliable to our design. The use of these transistors delivers simplicity and reliability to our design. The thermal limiting circuitry inside the LM395 will terminate the circuit should there be excessive amount of heat, protecting the battery from burning.

Underload protection

In designing undervoltage protection for a charging circuit intended for 18650 lithium-ion batteries, the primary objective is to prevent the battery from being over-discharged, which can lead to irreversible damage and compromise its lifespan. A typical implementation involves incorporating a dedicated undervoltage protection IC or circuitry that constantly monitors the battery's voltage level during discharge and charging cycles. When the battery voltage drops below a predefined threshold, indicating a critically low state of charge, the protection circuit triggers a disconnect mechanism to halt further discharge and protect the battery from damage. This safeguard ensures that the battery remains within safe operating limits, prolonging its lifespan and preventing potentially hazardous conditions. Additionally, integrated battery management systems (BMS) may include features such as automatic shutdown or alarm signaling to alert users when the battery reaches a low voltage condition, facilitating timely intervention and maintenance. By incorporating robust undervoltage protection mechanisms, the charging circuit can effectively preserve the health and integrity of 18650 lithium-ion batteries, promoting safe and reliable operation in various applications.

5.4.3 Reverse polarity protection

The uHAT's operation requires only a forward drop across all its components, if not protected from a reversed input this could burn, destroy, and saturates components. The input protection is modelled using a Power MOSFET connected to a Zener diode to maximise its efficiency. The power mosfet has a parasitic diode on its body which has a forward voltage drop of 1V, this is efficient because the voltage at the Drain (input) has to be always greater by at least volt to that of the source(output) in order for the circuit to conduct and allow current flow, furthermore a Zener diode ensures a regulated 1V at the source for current to flow from the gate to the source which would now mean that the voltage at the input has to be at least 2V greater than that of the source and this is how an reverse input polarity is achieved.

5.4.4 Voltage regulation

5.5 Results and Testing

5.6 Final design

5.7 Conclusion and Recommendations

Chapter 6

Conclusions

> The same rule holds for us now, of course: we choose our next world through what we learn in this one. Learn nothing, and the next world is the same as this one.
>
> —*Richard Bach, Jonathan Livingston Seagull*

The purpose of this project was to...

This report began with...

The literature review was followed in Chapter...

The bulk of the work for this project followed next, in Chapter...

In Chapter...

Finally, Chapter... attempted to...

In summary, the project achieved the goals that were set out, by designing and demonstrating...

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Appendix A

Appendix A4

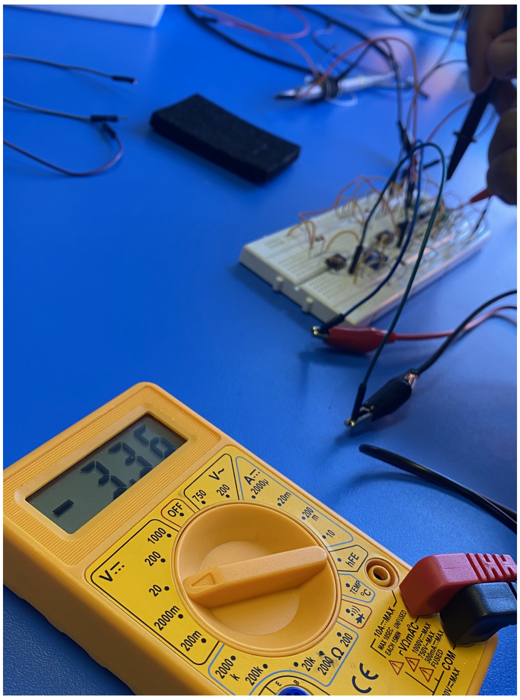

Figure A.1: Image of split supply test

Figure A.2: Image of Amplifier test when input is 1mV

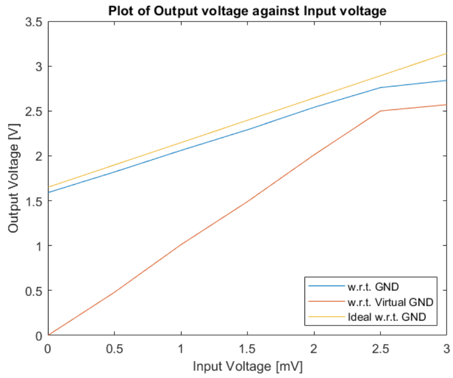

Figure A.3: Plot of Output voltage against input voltage from the oscilloscope

ELECTRICAL CHARACTERISTICS

Parameter	Conditions	LM195			LM395			Units
		Min	Typ	Max	Min	Typ	Max	
Collector-Emitter Operating Voltage (2)	$I_Q \le I_C \le I_{MAX}$			42			36	V
Base to Emitter Breakdown Voltage	$0 \le V_{CE} \le V_{CEMAX}$	42			36	60		V
Collector Current								
TO-3, TO-220	$V_{CE} \le 15V$	1.2	2.2		1.0	2.2		A
TO-5	$V_{CE} \le 7.0V$	1.2	1.8		1.0	1.8		A
Saturation Voltage	$I_C \le 1.0A$, $T_A = 25°C$		1.8	2.0		1.8	2.2	V
Base Current	$0 \le I_C \le I_{MAX}$ $0 \le V_{CE} \le V_{CEMAX}$		3.0	5.0		3.0	10	μA
Quiescent Current (I_Q)	$V_{be} = 0$ $0 \le V_{CE} \le V_{CEMAX}$		2.0	5.0		2.0	10	mA
Base to Emitter Voltage	$I_C = 1.0A$, $T_A = +25°C$		0.9			0.9		V
Switching Time	$V_{CE} = 36V$, $R_L = 36\Omega$, $T_A = 25°C$		500			500		ns

(1) Unless otherwise specified, these specifications apply for $-55°C \le T_j \le +150°C$ for the LM195 and $0°C \le +125°C$ for the LM395.
(2) Selected devices with higher breakdown available.

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Product Folder Links: LM195 LM395

Figure A.4: LM395 Electrical Specifications