Measuring jaw movement during sleep

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Project Summary

Obstructive Sleep Apnoea (OSA) is a sleep disorder which affects the lives of many people around the world. One of the causes of OSA is upper airway collapse. Past research has shown that the collapsibility of the upper airway increases when the mandible is protruded or the mouth is open. Therefore, the West Australian Sleep Disorders Research Institute (WASDRI) believes that there is a link between mandible position and the severity of OSA. Considering this, a system designed to measure mandible position would be helpful for the researchers at WASDRI. Currently, no such system exists for this particular purpose.

This project investigated many different approaches for building a jaw measurement device. A system which uses two Hall Effect Sensors (HES), an anisotropic ferrite magnet, two operational amplifiers and an Arduino microcontroller, is chosen to be the final design. A computer with Matlab installed calculates the jaw opening and jaw protrusion based on the voltage outputs of the sensors provided by the Arduino microcontroller. A prototype of the final system is built and tested on a custom built experiment rig, and it is proved that by using the voltage outputs of both sensors, both jaw opening and jaw protrusion can be calculated.

This project has made considerable progress in its objectives, but some tasks remained unfinished. Future works to be completed include completing human trials, integrating with the data logger at WASDRI, building a wireless interface and investigating the viability of other systems.
Letter of Transmittal

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7th November, 2011  

Winthrop Professor John Dell  
Dean  
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Dear Professor Dell  

I am pleased to submit this thesis, entitled “Measuring jaw movement during sleep”, as part of the requirement for the degree of Bachelor of Engineering.  

Yours Sincerely  

Wilfred Wong  
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Acknowledgements

I would like to take this opportunity to thank Professor Adrian Keating for his constant supervision and guidance throughout the duration of the project. His tireless enthusiasm towards the project over the year and the knowledge he provided proved to be critical to the completion of this work.

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Nomenclature

Acronyms
ADC - Analog-to-Digital Converter
CRT - Cathode Ray Tube
DAC - Digital-to-Analog Converter
ENCM - Engineering, Computing and Mathematics
HES - Hall Effect Sensor
IMU - Inertial Measurement Unit
OSA - Obstructive Sleep Apnoea
PPE - Personal Protective Equipment
REM - Rapid Eye Movement
SAIL - Sensors and Advanced Instrumentation Laboratory
SCGH - Sir Charles Gairdner Hospital
USB - Universal Serial Bus
UWA - University of Western Australia
WASDRI - West Australian Sleep Disorders Research Institute
1 Overview

1.1 Introduction
The aim of this project is to design, build and test a system to measure the jaw movement, particularly the jaw opening and jaw protrusion on a sleep apnoea patient. In addition to that, the aim of this project is to also integrate the output of this system with the pre-existing sleep monitoring system at the West Australian Sleep Disorders Research Institute (WASDRI) at Sir Charles Gairdner Hospital (SCGH). This project is being conducted with WASDRI in collaboration with the Sensors and Advanced Instrumentation Laboratory (SAIL) at University of Western Australia (UWA).

This project is part of a bigger project which aims to measure upper body position of a sleep apnoea patient. The data recorded will prove to be valuable to the researchers at WASDRI, who can then use the data collected to diagnose sleep apnoea or find the best sleeping posture for a patient.

The main issues faced in the process of developing a jaw measurement device is that the device will need to be as small as possible to avoid disrupting the sleep quality of the patient. The device will also need to be durable and safe. These constraints prompted the investigation of several different systems, which are described in the literature review.

Obstructive sleep apnoea (OSA) is a common sleeping disorder, affecting up to 4 percent of middle-aged adults (Victor 1999). OSA can be characterised by the partial or complete obstruction of the upper airway during sleep, which causes loud snoring, oxyhaemoglobin desaturation and frequent arousals, the consequences of which include depression, cardiovascular disease, hypertension and excessive daytime sleepiness (Walsh et al. 2008a). Population-based studies suggest that 2 percent of women and 4 percent of men in the middle-aged work force have symptomatic OSA (Young et al. 1993). According to Hillman in 2006, OSA and its consequences are estimated to result in significant financial cost of the Australian society, in excess of US$ 7 billion (Hillman et al. 2006). OSA even affects approximately 1-3% of the paediatric population (Pereira et al. 2008).
It is established that the upper airway is more likely to collapse when the patient is in a supine posture (Walsh et al. 2008a). Figure 1-1 shows the collapse of the upper airway. The elongated and enlarged soft palate creates an obstruction on the airway, thus preventing normal breathing of the patient. (Victor 1999)

![Figure 1-1: Obstruction of Upper Airway. Modified from (Victor, 1999)](image)

The relationship between mandible (lower jaw) position and upper airway cross-sectional area has been investigated, and it is shown that the maximum protrusion of the mandible results in a twofold increase in the upper airway cross-sectional area (Ferguson, Love & Ryan 1997). The collapsibility of the upper airway during sleep increases when the mouth opens (Meurice et al. 1996). The jaw opening and jaw protrusion causes the backward displacement of the tongue, thus narrowing the airway (Choi et al. 2000). It is therefore hypothesised that there is a link between head and mandible position and the severity of OSA (Walsh et al. 2008b)

This project aims to measure both jaw protrusion and jaw opening. Jaw protrusion is the jaw movement where the mandible slides out from its normal position, and the position of the maxilla (upper jaw) will be behind the mandible. Figure 1-2 shows the normal mandible position and the protruded position.

![Figure 1-2: Jaw Protrusion. Modified from (Lee 2010)](image)
Jaw opening is the movement in which the mandible rotates around the temporomandibular joint, which is the joint connecting the mandible and the maxilla, and causes the articulation of the mandible. The mandible and the maxilla hinges around the temporomandibular joint, and opening of the jaw is controlled by the lateral pterygoid, which is assisted by the three muscles which are located at the neck area: the digastrics muscle, the mylohyoid muscle and the geniohyoid muscle. (Gray 1918)

Figure 1-3: Muscles for Jaw Opening (Gray, 1918)

Figure 1-4: Jaw Opening. Modified from (El-Gohary 2008)
1.2 Literature Review

This project focuses on the measurement of the jaw movement in a sleeping position. After an extensive search, it is shown that there is currently no system that has that kind of capability. Most of the systems available only measured the jaw movement when the subject is in a certain position. Therefore, the literature review for this project focuses mostly on the different systems that are available, and by comparing the different capabilities and limitations of the systems, a viable solution for measuring jaw movement in a sleeping patient can be found.

Various systems had been utilised to study jaw movement throughout the year. There had been some research done on using mechanical devices, optical motion capture, fluoroscopic motion capture, electronic and telemetric methods, magnetometry and opto-electronic methods. (Soboleva, Laurina & Slaidina 2005) Several of these methods were reviewed in this project.

1.2.1 Optical/Motion Capture

There are some works done in the field of optical motion capture (Kinuta et al. 2005; Naeije, Van der Weijden & Megens 1995). A paper written in 2005 spoke of a system which uses a home digital camcorder to track jaw movements (Kinuta et al. 2005). The system was simple and as the only equipment needed was a digital camcorder, and the motion capture software was developed by the researchers. The system was said to be as accurate as a conventional jaw tracking system. Although so, this system was only able to track the jaw movement only when the subject was stationary, which poses a problem, as the patient in WASDRI will be turning about on the bed as the sleep study goes on.

Another system which was investigated was OKAS-3D, which used optical markers which was placed on the teeth (Naeije, Van der Weijden & Megens 1995). The system consisted of optical markers and two Cathode Ray Tube (CRT) screens which were placed perpendicular to each other. The system was able to detect six degrees of freedom, and was described as being accurate to within 0.27 mm in any dimension.
Despite all of these advantages and the efforts of the researchers, the system proved to be too bulky and expensive to be used in this project.

Most of the optical motion capture devices relied a lot on the subject to be stationary. Therefore optical motion capture was dismissed as an option for this project.

1.2.2 Telemetry

Another methodology that was investigated was systems that use telemetry to record mandibular posture. A system proposed in 1969 used miniaturized inductive transducers to measure the mandibular position of a subject (Thomson & MacDonald 1969). The system consisted of a coil which was inserted into the substance of an artificial tooth in one jaw and a metallic tooth surface which was provided on an opposing tooth.

![Figure 1-6: Transducer and Metallic Tooth Surface for Telemetry System (Thomson and MacDonald, 1969)]
A disadvantage of this system was that it was limited in terms of range. In this system, it could measure not more than 5 mm of displacement, which is too limited for this project. The placement of an artificial tooth also presented another problem, as most patients at the sleep clinic would not agree with replacing a tooth of their own with an artificial one.

Another system which investigated the usage of telemetry was proposed by Griffiths in 1975 (Griffiths 1975). The system uses a miniature transmitter which was powered by a battery mounted in a tooth gap and metal fillings on a tooth at the opposite jaw to measure the jaw opening. The location of the transmitter and the metal milling is shown in Figure 1-7. The receiver was basically a frequency meter, and the output of the receiver was non-linearly proportional to the interocclusal distance.

![Transmitter and Metal Filling for Telemetry](image)

**Figure 1-7:** Transmitter and Metal Filling for Telemetry (Griffiths, 1975)

This system is one of the first to show that it is possible to implement a wireless interface. By using a battery and a transmitter, it is possible to transmit the data collected without using wires, therefore improving the sleep quality of the subject. However, this system only measured situations where the displacements are limited, which include rest, work and swallowing. It also does not differentiate between jaw opening and jaw protrusion. However, it does raise some interesting points on wireless interfaces.
1.2.3 Inertial Measurement Unit

Another system which was proposed to be a possibility was a system which used Inertial Measurement Units (IMU) to measure jaw movements. IMU was used in another related project which measures body position of a sleeping patient (Fry 2011), but the system that was implemented for measuring upper body position proved to be too inconvenient for measuring jaw movements.

A paper on the development of an ultra-miniaturized IMU for measuring jaw movement was looked into (Lin et al. 2010b). This particular system, named WB-3 measures jaw movement during free chewing by using an IMU that contained a tri-axial gyroscope, a tri-axial accelerometer and a tri-axial magnetometer. This system was further developed into WB-4, which had an additional Bluetooth module, which enables the transfer of data wirelessly to the computer (Lin et al. 2010a). In addition to that, instead of attaching only one IMU on the chin, the new system used two IMUs, placing an additional IMU on the subject’s forehead. The addition of the second IMU was to compensate for the head movement of the subject. The total weight of the system was 7 grams, and the total size of the housing of the whole system is 37 mm x 23 mm x 12 mm.

**Figure 1-8:** Comparison between Inertial Measurement Unit Systems and Placement Location (Lin et al. 2010b; Lin et al. 2010a)
This system demonstrated the possibility of using IMU to measure jaw movement. Although the system has compensated for the head movement by adding a second IMU, it does not compensate for body position. In addition to that, this system was developed to measure jaw movement during chewing, which has a very limited jaw opening. Even so, it was a viable solution, as it was able to detect both the jaw protrusion and the jaw opening. The addition of a Bluetooth module as a means for transferring the data wirelessly is something that can be considered in this project.

1.2.4 Magnetometry

The next few systems that were investigated were systems that used magnetic devices as a means to measure jaw movement. Different types of magnetic devices are available, one of which is the Hall Effect Sensor (HES). A HES is a device which was invented by Edward Hall, and it outputs a voltage output that is inversely proportional with the distance between the HES and a magnet. (Ramsden 2006)

Measuring jaw movement using magnetic devices had been used in the past on animals. Deich and his team used a HES to detect jaw movement on a pigeon (Deich, Allan & Zeigler 1984). Two holes were drilled along the mandible, and a screw was inserted in each hole. The magnet was then glued in between the screws, followed by the attachment of the HES. Great care was taken to make sure that the HES and the magnet is centred and perpendicular to the magnet. The setup can be viewed in Figure 1-9.

![Figure 1-9: Hall Effect Sensor System on Pigeon (Deich et al., 1984)]
This method was not really applicable in this project, as it was easy to attach the magnet and the sensor to the maxilla and mandible of a pigeon respectively. This will probably not be the case in a human, as there is no way to attach it in a human mouth in that manner. An alternative will probably be attaching the HES at the exterior of the mouth, and placing the magnet within the mouth.

Another system was designed in 1994, which used magneto-resistive detectors to measure jaw movement (Dove et al. 1994). The magnetic field sensors were arranged as a detector array, and a support system was needed to hold the subject in place, whose head was held in the frame using vacuum cushions. This means there was little to no mobility on the subject’s head, thus this system was deemed unfit to be used in this project. It does open to a possibility of using multiple sensors in the system, which will provide a more accurate reading of the jaw movement. The system can be seen in Figure 1-10.

![Figure 1-10: Detector Array and Support System (Dove et al., 1994)](image)

Another research which used sensor arrays to track jaw movement used 2 neodymium magnets and 32 elements of two-axial fluxgate sensor array (Yabukami et al. 2002) (Yabukami et al. 2003). This system attached the magnets on the head portion and the front tooth of the subject. Essentially, the magnetic field of the magnets that were attached to the subject’s head and tooth was detected by the 32-element sensor array.
This was a very intriguing idea, as although the system required the patient to be directly in front of the sensor array, it is possible to modify the system to include more sensors and uses detect the jaw and head movement. But in order to implement a similar system, the calculation required will be very complex, and is out of the scope of this project.

A system was proposed to measure the mandibular distortion during jaw movements in human, using a micro magnetic sensor and a permanent magnet (Horiuchi et al. 1997). The system proved that the mandible and the dental arch distort during jaw movements because of the contraction of the jaw muscles. Although this was not something this project will be delving into, it is worth considering when using an intraoral system, and selecting the placement of the sensors. This research also provided with a basic procedure in measuring vertical and horizontal jaw displacement.

A simple and inexpensive system for monitoring jaw movement was proposed in 2002, using two accelerometers, one HES and one magnet (Flavel, Nordstrom & Miles 2002). This system was further used in another research on measuring the stability of the mandible.
during locomotion (Flavel, Nordstrom & Miles 2003). Two single-axis accelerometers were used to measure the acceleration and position of the mandible. The disadvantage of using a pure accelerometer system is that the system would not have given a good result when the jaw is at a static position. Therefore, an additional system was introduced in the form of HES and magnets. The HES complimented the accelerometer system by providing a near-stable output at static jaw position. The system concept was shown in Figure 1-12.

![Accelerometers and Hall Effect Sensor system](image)

**Figure 1-12:** Accelerometers and Hall Effect Sensor system (Flavel et al., 2002)

The system consisted of two parts: the maxillary part and the mandibular part. The mandibular part consisted of a HES and an accelerometer, while the maxillary part consisted of a neodymium magnet and an accelerometer. The neodymium magnet was set to be aligned perfectly with the HES, in order to get a better measurement of the static position of the jaw. The system was attached to the teeth by using glass ionomer dental cements. This system was capable of providing real-time output, and was able to match commercially available optical tracking systems. Although so, there were still some limitations for this system. For instance, this system was only capable of measuring jaw opening and not jaw protrusion. This system however opened up a possibility of intraoral jaw measurement.

Many of the systems described above mainly measured jaw opening only, and this project required jaw protrusion to be detected as well. A system that was devised to record mandibular position during nocturnal bruxism used two pairs of magnetic reed switches and 2 samarium-cobalt magnets (Akamatsu, Minagi & Sato 1996). A magnetic reed switch
consists of a pair of contacts on metal reeds which close up when a magnetic field is present (Gurevich 2006). In this case, the magnetic reed switch stayed on when the switch and the magnet were close to each other, and switched off when the switch was more than 2.65 mm away from the magnet. Figure 1-13 shows the position of the magnet and the reed switch.

![Magnet and Reed Switch to Measure Jaw Protrusion](image)

**Figure 1-13**: Magnet and Reed Switch to Measure Jaw Protrusion (Akamatsu, Minagi & Sato 1996)

Although this system might be enough for recording when nocturnal bruxism occurs, it was not enough to fulfil the requirement of this project. This project needed the jaw protrusion to be measured as it changed, while this system only records a change when the distance between the magnet and the switch reaches a certain point. It might be possible to change the magnetic reed switch to a linear HES, as a linear HES will be able to provide a continuous flow of data. Although this system did not investigate jaw opening, it help provide the extent of protrusion of an intraoral device that would be allowed in a subject’s mouth without him/her feeling any discomfort.

Perhaps the most important paper that was found was the paper on measuring mandibular posture during sleep in healthy adults (Miyamoto et al. 1998). This project was performed on sleeping subjects, and this related to this project closely. This system used one magnet and one HES, which were attached onto the subject’s teeth by using retainers. The magnet
and the HES were attached to the retainer using acrylic compounds, and they were arranged so that the magnet was directly above the HES when the mouth was closed. An additional posture sensor was attached to the subject’s body to detect the subject’s body position during sleep.

Figure 1-14 shows the position of the HES and the magnet in the mouth. The HES and the magnet were attached onto the mandible and maxilla respectively by using orthodontic retainers.

![Image of Hall Effect Sensor and Magnet Position](image)

**Figure 1-14:** Hall Effect Sensor and Magnet Position in Sleeping Position (Miyamoto et al. 1998)

It was shown that the magnet sensor was able to detect the magnet’s magnetic field up till more than 10 mm, and it showed the general distribution of mandible position for a sleeping subject, where it was shown that the jaw opening was mostly distributed below 5 mm. This system was the first system to divide vertical mandible position into different stages of sleep. The mandible was shown to be more open more often during the Rapid Eye Movement (REM) stage than other sleep stages.

Although this system was able to collect vertical mandible opening to a certain degree of accuracy, it was unable to address the protrusive movement of the mandible. This can be compensated if an additional system such as the system mentioned above using magnetic
reed switches. Another possibility is to introduce a second Hall Effect Sensor, and by using basic trigonometry, both jaw opening and jaw protrusion can be calculated.

In addition to that, the introduction of intraoral appliances might have affected the sleeping quality of the subject. Although the effect of intraoral appliances is less than attaching a bulky system on the patient, the effect cannot be neglected. Therefore, a design constraint on the size of the system needed to be implied, and it should be as small as possible.

1.3 Objectives

The objectives of this project were:

- to design, build and test a system to measure jaw movement
- to develop a computer model to calculate the jaw opening and jaw protrusion
- and to integrate with the data logger system at WASDRI

These objectives were undertaken with the overall aim to measure upper body position of a sleep apnoea patient, including the head, jaw and chest positions.

To date, no such system has been implemented in the manner proposed. If this system was able to be implemented successfully, it will be able to provide valuable data to the researchers at WASDRI, and they can use the data for various purposed, which include:

- diagnosing sleep apnoea on a patient
- quantifying sleeping posture of a patient
- and finding the best sleeping posture for a sleep apnoea patient, so that sleep apnoea occurrence can be reduced

This project aims only to design the jaw movement measuring device, and further research by future students will be required to optimise the system. The documentation on the design, build and testing methods used for this project will provide a solid foundation for future students to build upon.
1.4 Organisation

Chapter 2 details the design and selection process for the jaw measuring device. The design process covers the design criteria and the softwares used for this project. The selection process details the justification of design choices that were made. The selection process covers the selection of the components needed for the fabrication of a prototype of the final system. The experimental setup for the selection process and for testing the final prototype was then discussed. Finally, safety considerations relating to the design and fabrication of the final prototype are presented.

Chapter 3 is a discussion of the results obtained. The results of a test performed using a prototype of the final system and the experimental setup proposed in Chapter 2 were analysed and discussed. The effect of the experimental setup on the testing stage was also discussed. Finally, the results for this setup were compared to previous research.

Chapter 4 gives a summary of final design, and made assessment on the progress of the project in terms of the project objectives. Future work was also recommended, based on unresolved issues during the project and further improvement on the final design.
2 Design Approach & Experimental Method

2.1 Design Criteria

2.1.1 Safety

A project of this nature must place safety above all else in making design decisions. The occurrence of hazards such as choking on wires or the device itself should be minimised as much as possible. This can be done by attaching the system to the patient firmly in order to prevent the patient from swallowing the device. Wires are placed in a configuration which is designed to avoid wrapping around the patient and choking. All sharp edges are to be surrounding by epoxy to prevent cuts or poking injuries. Lead free solders are used in building the system which will be attached in the patient’s mouth so that the patient will not get lead poisoning. This is also in accordance to the Restriction of Hazardous Substances Directive (European Union 2003).

2.1.2 Size

The jaw measuring device will need to be attached to the patient; therefore the size of the system is designed to be as small as possible. The patient already has to wear several other devices on their face, and the smaller the new system is, the patient will feel less discomfort, and thus providing a more reliable set of data for WASDRI. Figure 2-1 demonstrates the lack of space and emphasises the need for a compact and unobtrusive system.

![Figure 2-1 Current Setup at Sleep Clinic (Crocker 2010)](image-url)
This constraint limits most of the systems investigated in the literature review, such as the sensor array systems. The HES system which was intra-oral (Miyamoto et al. 1998) would prove to be very convenient. Since the HES system is very small in size, it does not obstruct other equipments which were attached to the patient.

2.1.3 Durability

The system is expected to be used constantly and thus needs to be able to withstand the wear and tear caused by everyday use. It should also be able to withstand the disinfection which is performed on instruments at WASDRI after each use. This further emphasises the need of epoxy to seal up the system in order to preserve the functionality of the system.

2.1.4 Speed

This is not a grave issue as it is static position and not movement that is being recorded. Each sleep study lasts for approximately 8 hours. The amount of data points that would be collected for a given frequency, \( f \) is calculated by using Equation (2.1).

\[
\text{Amount of data} = \frac{1}{f} \text{Unit/s} \times \frac{60}{1} \text{ s/min} \times \frac{60}{1} \text{ min/hr} \times 8 \text{ hr} = \frac{28800}{f}
\]  

(2.1)

A frequency of 1 Hz will produce 28800 data points, which should be enough to represent the jaw movement of a patient in the sleep study.

2.1.5 Sensitivity

Currently, there is no existing system to measure jaw movement at WASDRI. It is hoped that the sensor system will be able to provide a resolution of approximately 0.5 mm for the first 20 mm jaw opening, and a resolution of 1mm for the next 20 mm.

2.1.6 Compatibility

Currently, WASDRI has two different data acquisition systems, which were used for research and day-to-day diagnostics. The two systems were Chart® by ADInstruments®
and a Compumedics® E-Series system. Chart® is a much superior recording system compared to Compumedics®, but it is only used for research purposes only. Compumedics® is used for day-to-day diagnostics. It is desired that the system that was designed incorporate a microcontroller, which will be used to collect the data, do the necessary calculations and return the required information as a single value (Crocker 2010).

Figure 2-2: Screenshots from Chart® (top) and Compumedics® system (bottom) (Crocker 2010)

2.1.7 Cost

While the system is not required to be mass-produced at the time of the design, and there is no tight budget on the project, it is advised that the system should be as inexpensive as possible so that it can be reproduced at other sleep clinics which may have an interest in implementing the system for themselves.
2.1.8  Reliability

In order to provide reliable data for WASDRI and other possible implementers, the system will need to be reliable and easy to use. In regards to that, a full user manual outlining the safety protocols and correct assembling methods is expected to be deployed along with the system.

2.2  System Design

The system that was chose to be implemented is a modified system of Miyamoto’s team (Miyamoto et al. 1998), but instead of using just one HES, this project will be using two HESs. This design aims to measure displacement of the mandible in two different orientations, which are described in Figure 2-3. The displacement measured in the X direction represents jaw protrusion, and the displacement measured in the Y direction represents jaw opening.

![Orientation of Sensor System](image)

**Figure 2-3:** Orientation of Sensor System. Modified from (El-Gohary 2008)

The main reason behind choosing HESs instead of any other systems investigated in the literature review was the size advantage. Compared to most systems investigated, HES systems are usually very small, except for the systems which utilised sensor arrays. The
proposed system of using two HESs and one magnet for measuring jaw movement would be small enough to be attached to the patient’s teeth, thus removing the need of additional electrical equipments around the patient’s body. Being intra-oral, there would be minimal influence on the sleep quality of the patient.

By using one HES, Miyamoto and his team had only one voltage output, and by applying the voltage output to a lookup table or an equation, they got a distance, which they assumed was the jaw output. That was not the case, as explained in the literature review. By using two HESs, this project attempts to use the second HES to collect another voltage output, and by applying the two voltage outputs to two separate lookup tables, the distances for each HESs with respect to the magnet can be obtained. The two HESs are labelled A and B, with A being the one placed further inside the mouth, and B being the one near the mouth opening. The distances obtained for both sensors are labelled \(d_1\) and \(d_2\), where \(d_1\) is the distance from A to the magnet and \(d_2\) is from B to the magnet.

It is theorized that the distances \(d_1\) and \(d_2\) could be found by calibrating the sensors in a controlled environment. The calibration is done by recording the distance from the HES to the magnet in relation to the voltage output for a HES when the magnet is placed directly in front of the HES. Two lookup tables were then constructed, one for each sensor, which allowed the author to determine the distance between the HES and the magnet depending on the voltage output of the sensor.

According to Cosine Rule, given the lengths of each side of a triangle, all the angles in the triangle can be found. By calculating the displacements in X and Y directions for each HES and averaging the values, the displacement in the X and Y direction for the midpoint of the two sensors can then be found.

Figure 2-4 shows the proposed position for the system, with the sensors attached to the maxilla and the magnet attached to the mandible.
Angle $\alpha$ is defined as the angle between line AB and line AM, and angle $\beta$ is defined as the angle between line AB and line BM.

The main thing to remember when finding angle $\alpha$ and angle $\beta$ is to follow the following steps (Herzog 2005):

1) Calculate the largest angle using Cosine Rule. The largest angle is the angle corresponding to the longest line.
2) Find the second angle by using Sine Rule, as it is less complicated.

Three possible orientations of the HES system were investigated. They were:

1) When angle $\alpha$ and angle $\beta \leq 90^\circ$
2) When angle $\alpha \leq 90^\circ$ and angle $\beta \geq 90^\circ$
3) When angle $\alpha \geq 90^\circ$ and angle $\beta \leq 90^\circ$

The calculations for each of these three orientations can be found in Appendix A. For each scenario, the calculation for displacement in x and y directions are different, as there is a need to consider the cases where both the sensors are on the left or right side of the magnet.
Figure 2-5 shows the magnified version of triangle ΔABM, and the angles within the triangle. x1 and x2 represents the distance in the X direction from A and B to the magnet respectively, and y1 and y2 represents the distance in the Y direction from A and B to the magnet respectively. The distance between the HESs, d is designed to be 8 mm.

![Diagram of triangle ΔABM with labels for angles and distances]

**Figure 2-5: Detailed version of ΔABM**

The calculations for finding the jaw opening and jaw protrusion when \( \alpha \) and \( \beta \leq 90^\circ \) are described in Equations (2.2) to (2.9). The calculations for finding the jaw opening and jaw protrusion when either \( \alpha \) or \( \beta \geq 90^\circ \) can be found in Appendix A.

\[
\begin{align*}
\text{If } d_1 > d_2 & \quad \alpha = \arccos \left( \frac{d^2+d_2^2-d_1^2}{2d_1d_2} \right) \quad \beta = \arccos \left( \frac{d^2+d_1^2-d_2^2}{2d_1d_2} \right) \\
\text{If } d_2 > d_1 & \quad \alpha = \arcsin \left( \frac{d_1 \cdot \sin(\alpha)}{d_2} \right) \quad \beta = \arcsin \left( \frac{d_2 \cdot \sin(\beta)}{d_1} \right)
\end{align*}
\]

\[
\begin{align*}
x_1 &= d_1 \cdot \cos(\alpha) - \frac{d}{2} \\
x_2 &= \frac{d}{2} - d_2 \cdot \cos(\beta) \\
y_1 &= d_1 \cdot \sin(\alpha) \\
y_2 &= d_2 \cdot \sin(\beta) \\
x &= \frac{x_1 + x_2}{2} \\
y &= \frac{y_1 + y_2}{2}
\end{align*}
\]
When the jaw opens, the mandible rotates about the temporomandibular joint, as explained in Figure 1-4. Therefore, the mandible and the maxilla are angled instead of being parallel. Figure 2-6 represents the entire setup with relation to the temporomandibular joint, where JA and JB are the distances between the joint and HES A and HES B respectively, JK is the vertical distance from joint to maxilla and $d\theta$ is the angle of jaw opening.

![Figure 2-6: Representation of the whole system in relation to the temporomandibular joint](image)

By using a combination of Cosine Rule and Sine Rule, we can get the $d_x$ and $d\theta$ values for the two different HESs. In order to get a better estimate, an average of the two angles of opening $\theta_{ave}$ can be found. $d\theta$ is found by subtracting an initial angle $\theta$ from $\theta_{ave}$. The calculation is described in Equations (2.10) to (2.16).

\[\gamma = 180^\circ - \alpha\]  \hfill (2.10)
\[d_{x1} = \sqrt{AK^2 + d_1^2 - 2 \cdot d_1 \cdot AK \cdot \cos(\gamma)}\]  \hfill (2.11)
\[\theta_1 = \arcsin \left( \frac{d_1 \cdot \sin(\gamma)}{d_{x1}} \right)\]  \hfill (2.12)
\[d_{x2} = \sqrt{BK^2 + d_2^2 - 2 \cdot d_2 \cdot BK \cdot \cos(\beta)}\]  \hfill (2.13)
\[\theta_2 = \arcsin \left( \frac{d_2 \cdot \sin(\beta)}{d_{x2}} \right)\]  \hfill (2.14)
\[\theta_{ave} = \frac{\theta_1 + \theta_2}{2}\]  \hfill (2.15)
\[d\theta = \theta_{ave} - \theta\]  \hfill (2.16)
2.3 Selection Process

2.3.1 Selection on HES

The selection of the HES is of the utmost importance, as it affects directly to the range in which the sensor is capable of measuring. The range in which the HES can detect the magnetic field of the magnet is proportional to the sensitivity of the HES. The method that was employed to compare the different sensors is by using the experiment rig which is described in Figure 2-7.

Figure 2-7: (a) Solidworks Drawing of Experiment Rig and (b) Photo of Constructed Experiment Rig

The micrometers used for building this experimental rig are double-row ball bearing linear stage from Oriel Corp of America with a maximum range of 9 mm and 13 mm. Therefore,
by combining the two stages, the magnet rig is able to move 22 mm in small increments accurately. This can be done by rotating the two micrometers attached to the stages. After moving 22 mm, the magnet rig is moved by hand by 1 mm increments, by using a graph paper as a reference. The sensors are placed directly in front of the magnet separately, and the voltage outputs of the sensors are measured.

Two different HESs, SS495A1 and UGN3503U are tested by using the same magnet. An INA125P instrumental amplifier is used for this test, and a differential amplifier configuration is employed to increase the range from 2.5V – 5V to 0V – 5V.

**Comparison between Sensor**

From Figure 2-8, it can be seen that SS495A1 has an advantage over UGN3503U. The important distance is between 5 mm to 40 mm, and from the graph above, SS495A1 produces a greater voltage output. The voltage output needs to be high enough to be discernible by an Arduino microcontroller, which is selected for this project - this microcontroller can detect voltage from the range of 0V to 5V, and it converts the voltage to an Analog-to-Digital Converter (ADC) value from 0 to 1023, with each ADC value representing 5 mV. Therefore SS495A1 is chosen over UGN3503U as the better HES.

Figure 2-8: Comparison between Hall Effect Sensors SS495A1 and UGN3503U
2.3.2 Selection of Magnets

The magnet is required to be as small as possible, so that it can be placed in the patient’s mouth without causing any discomfort. The selection of the magnets is done by using the same experimental procedure for the HES selection, except that instead of changing the sensors, an SS495A1 HES is used and different magnets are evaluated. The magnets that are tested are a disc-sized anisotropic ferrite magnet which is 10 mm in diameter and 3 mm in thickness and a rectangular neodymium magnet which is 3 mm in width, 3 mm in length and 4 mm in height. An INA125P instrumental amplifier is also used for this test, in the same configuration as the selection of sensors.

![Comparison between Magnets](image)

**Figure 2-9:** Comparison between Magnets

As shown in Figure 2-9, the disc-sized magnet produces a greater voltage output than the rectangular magnet between 5 mm and 40 mm, which is identified as the important distance at the previous experiment. Therefore, the disc shaped magnet is chosen over the rectangular magnet as the better magnet.
2.3.3 Selection of Amplifier

In this design, only the positive magnetic field needs to be detected, but since the range of voltage output of the HES in the positive magnetic field is 2.5 V – 5 V, only half the measurement range of the Analog-to-Digital Converter (ADC) values on the microcontroller is being used. It is desired to bring the voltage within the range from 0V to 5V. Therefore, a differential amplifier circuit was used to subtract 2.5V from the output and a gain was applied to amplify the subtracted output. The resultant circuit was as below:

![Differential Amplifier Circuit](image)

Figure 2-10: Differential Amplifier

The output voltage of the differential amplifier is calculated by using Equation (2.17).

\[
V_{out} = \frac{R_2}{R_1} (V_{in} - 2.5) \quad (2.17)
\]

A voltage divider which used two resistors with the identical values was used to provide a voltage reference of 2.5V. The voltage divider was provided 5V as the voltage input, and thus 2.5V can be obtained between the resistors.

Different types of amplifiers were chosen to be tested. INA125P is a dual supply instrumentation amplifier with different voltage references. LM324 is a single supply quad operational amplifier, which contains 4 same operational amplifiers.

The INA125P was used in initial testing, but was later dismissed as a candidate, as it requires both a positive and a negative rail supply, and the power supply that would be use
in this project would only have a positive supply. Therefore LM724 was chosen as the amplifier for this project.

A trial and error method was applied for finding the correct gain for the circuit. The correct gain is defined as a gain which results in the voltage output of the sensor being saturated at a distance of 5 mm. The gain, $G$ is calculated by using Equation (2.18).

$$G = \frac{R_2}{R_1}$$  \hspace{1cm} (2.18)

The drop-off point is defined as the maximum distance at which the voltage output is saturated at the maximum voltage output for a given gain used for this circuit. 5 mm is defined as the optimal drop-off point, as it is the designed separation between the sensor system and the magnet.

Table 2-1 shows the gain and the different drop-off point by different gains used alongside the SS495A1 HES with a LM324 as the amplifier.

<table>
<thead>
<tr>
<th>R1 (kΩ)</th>
<th>R2 (kΩ)</th>
<th>Gain G (kΩ/ kΩ)</th>
<th>Drop-Off Point (mm)</th>
<th>Deviation from 5 mm (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.5</td>
<td>6.8</td>
<td>4.53</td>
<td>6</td>
<td>+1</td>
</tr>
<tr>
<td>1.5</td>
<td>15</td>
<td>10</td>
<td>15</td>
<td>+10</td>
</tr>
</tbody>
</table>

**Table 2-1** Drop-off point of Amplifier Depending on Gain

Therefore a gain of 4.53 was chosen for the smaller deviation from optimal drop-off point, and resistors of 1.5 kΩ and 6.8 kΩ were chosen.

### 2.3.4 Selection of Voltage Regulator

A voltage regulator which would be able to produce a constant supply of 5V was needed for this system. The voltage regulator was added to the circuit in order to prevent a voltage overload to the circuit during testing. The most common 5V voltage regulator is LM7805A and it was widely used because of its stability. An input voltage of 9V was supplied to the
LM7805A from a 6LR61-9V battery, which has a battery capacity of 565 mAh, and the voltage regulator outputs a stable 5V to the system.

The current usage of the entire circuit, which includes two SS495A1 HESs, one LM7805A voltage regulator and one LM324 amplifier, is 16.6 mA, and by using the current usage, the time limit in which the battery needs to be changed in order for a steady 5V to be provided to the circuit can be deduced. The battery life can be calculated by using Equation (2.19).

\[
\text{Battery Life} = \frac{\text{Battery Capacity}}{\text{Current Usage}} = \frac{565 \text{ mAh}}{16.6 \text{ mA}} = 34 \text{ hours} \quad (2.19)
\]

34 hours is more than sufficient if the final design is to be used in sleep trials, which usually lasts for 8 hours, provided the battery is changed every 3 or 4 trials.

2.4 Final System test

2.4.1 Experimental Rig

By using the experimental rig presented in Figure 2-7, the final system can be tested. The sensor system is placed at the same level as the magnet, and by moving the magnet rig, the voltage outputs of the sensors can be measured.

2.4.2 Articulator

After the system is built, an articulator will be used to test the accuracy of the system. The articulator is built by using an articulator system and two teeth models which are provided by Professor Mithran Goonewardene from the School of Dentistry. The teeth models are attached onto the articulator system by using plaster of Paris. The procedures for attaching the teeth models to the articulator system are described in Appendix B.

The articulator acts as a representation of the final system, showing how the final system would be attached to a patient’s teeth. It also simulates a patient’s teeth movement when opening the jaw, thus determining the needed range of the system.
Figure 2-11 details the specification of the articulator and the constructed version. The angle $d\theta$ in Figure 2-11(a) is the angle specified in Figure 2-6 which represents the angle of opening of the jaw.

Figure 2-11: (a) Articulator Design and (b) Constructed Articulator
2.5 Design Tools Employed

Solidworks® is used to design the experiment rig and the sensor system. The dimensions are thought out on paper, and finalised on Solidworks®. By using Solidworks®, a 3-D representation of the build can be visualised and thus identify flaws which are undetectable on paper.

Matlab® is used to analyse the voltage outputs from both HESs. It is also used during the calibration test to construct the lookup table for each sensor. This is further explained in the results and discussion section.

Schematic diagrams for the electrical circuits that are used in this project are first designed on Microsoft Office Visio, and testing is done on the breadboards before finalizing the design on stripboards. The safe operating procedures of soldering the electrical components onto the stripboard are detailed in Appendix C.

Microsoft Excel is used to record and analyse the collected data. In-built functions such as value averaging and graph drawing are used in the duration of the project.

2.6 Safety

Engineering projects of any nature involve hazards of varying severity in consequences. As such, safety should always be the first thing to cross the mind of any engineer. In this project, the safety of the laboratory in which the devices are designed and tested and the patient’s safety are of the utmost importance. Potential hazards were identified early in the project by performing risk assessment and measures were implemented to reduce or eradicate possible risks.

The majority of work for the project is completed at the Sensors and Advanced Instrumentation Laboratory (SAIL), which is located in the Engineering, Computing and Mathematics Building (ENCM) at UWA. A safety induction for the laboratory was given by Professor Adrian Keating at the commencement of the project, and several potential
hazards were identified and measures were outlined to prevent harm. A copy of the induction is shown in Appendix D.

This project focuses on the design and build of a jaw measuring device that uses two Hall Effect Sensors, which are encompassed in epoxy putty. The majority of the project focuses on the building of the electrical circuit for the sensor system. The circuit is built on a Vero Type Stripboard using a soldering iron to attach electrical components to the board.

The laboratory houses concentrated chemicals for the use of printed circuit board manufacturing. Unless proper safety induction is provided by the supervisor, unauthorized personnel are not permitted to approach the chemicals. If needed, the emergency first aid kit is located nearby, as shown in Figure 2-12.

![Emergency Exit and Fire Extinguisher Location](image)

**Figure 2-12:** Emergency Exit and Fire Extinguisher Location

Due to safety issues, it is not permitted for any personnel to work after hours or during weekends alone in SAIL. Another authorized SAIL personnel should be present. This is to avoid accidents from happening without anyone knowing about it. The SAIL community is a tight-knitted group, and therefore different communication methods are exchanged. Should there be any problem, it is encouraged to seek help. Emails and telephone numbers are exchanged among SAIL personnel in order to facilitate communication.
Any personnel who is last to leave the laboratory is required to make sure all electrical equipments are switch off. Exceptions are made to the equipments that are required to run throughout the night, which are required to be labelled properly.

In the event of an evacuation for incidents such as fires or chemical spillage, all personnel in the lab should evacuate in an orderly fashion. All items are to be left behind and personnel are to be evacuated to car park 15 of UWA. No personnel are allowed back in the building until instructed by an Area Warden.

The risk assessment for this project is categorized into two sections: working in the lab and working with the prototype. Tables 2-2 and 2-3 identified the hazards that were possible to happen while working in the lab and working with the prototype respectively, and an assessment on the risk for each hazard was performed. The risk measure is evaluated based on the consequence and likelihood of the risk (Trevelyan 2011), with the categorization of each being presented in Appendix E.

### 2.6.1 Working in the Lab

<table>
<thead>
<tr>
<th>Identified Hazards</th>
<th>Injury caused by entrapment of limbs in machinery, such as hot press machine and drill press</th>
</tr>
</thead>
</table>
| Causes             | 1) Loss of awareness when moving around the lab
<p>|                    | 2) Standing too close to operating machinery |
| <strong>Risk Measure</strong>   | <strong>High Risk</strong> (Consequence: Major; Likelihood: Possible) |
| Control Measures   | It is required that the hot press not to be operated unless proper training was provided. In an emergency, the emergency stop button should be pressed in order to stop the machine. It is also advised that when the hot press is being operated, a minimum of 1m proximity should be kept. Extra supervision is also recommended if available when operating machinery. |</p>
<table>
<thead>
<tr>
<th>Identified Hazards</th>
<th>Electrocution from electrical appliances in the laboratory</th>
</tr>
</thead>
<tbody>
<tr>
<td>Causes</td>
<td>1) Servicing or altering electrical appliances without proper training or authorization</td>
</tr>
<tr>
<td></td>
<td>2) Improper insulation on cables or wires</td>
</tr>
<tr>
<td><strong>Risk Measure</strong></td>
<td><strong>High Risk</strong> (Consequence: Major, Likelihood: Possible)</td>
</tr>
</tbody>
</table>

### Control Measures

- All mains-powered-supplied appliances may only be serviced or altered by authorized personnel. It is forbidden to use mains power supply for the project unless it is authorized by the supervisor.
- Proper insulation on all cables and wires are needed in order to prevent electrocution from happening. If insulation on a cable was damaged, authorized personnel should be informed in order to get the appliance back in working order. Until then, the appliance should not be used.
- All faulty appliances should be labelled clearly in order to prevent accidents from happening.

<table>
<thead>
<tr>
<th>Identified Hazards</th>
<th>Injury resulting from tools, including tripping on tools, cuts from tools with sharp edges or heavy tools dropping on foot</th>
</tr>
</thead>
<tbody>
<tr>
<td>Causes</td>
<td>1) Loss of awareness when moving around the lab</td>
</tr>
<tr>
<td></td>
<td>2) Untidy lab with tools lying around dangerously</td>
</tr>
<tr>
<td><strong>Risk Measure</strong></td>
<td><strong>Medium Risk</strong> (Consequence: Minor; Likelihood: Almost Certain)</td>
</tr>
</tbody>
</table>

### Control Measures

- All equipments in the laboratory should be arranged neatly in the boxes provided in order to avoid confusion.
- To prevent unnecessary injuries, all equipments with sharp edges, such as modelling knives will need their sharp edges covered.
- Covered shoes are needed in the lab, and any personnel found not wearing closed shoes will be asked to leave the laboratory.
- Other personal protection equipments, such as safety glasses should be worn whenever appropriate.
Identified Hazards: Fire in the laboratory

Causes:
1) Frayed wire can arc and start a fire
2) Smoking in the laboratory

**Risk Measure**: Medium Risk (Consequence: Catastrophic, Likelihood: Unlikely)

Control Measures:
- No smoking is allowed in the laboratory or anywhere in the building.
- Frayed wires should be labelled and decommissioned. In the event where smoke was detected or the fire alarm rang, all personnel in the laboratory should evacuate the building, using the emergency exit route as stated in Figure 2-12. All SAIL personnel were trained to identify and use different types of fire extinguisher.

---

Identified Hazards: Injury due to chemical spill

Causes:
1) Lack of concentration
2) Chemical placed at an unsafe place, and easy to get knocked over

**Risk Measure**: Medium Risk (Consequence: Moderate, Likelihood: Unlikely)

Control Measures:
- Unless proper safety induction was provided by the supervisor, unauthorized personnel are not permitted to approach the chemicals. If needed, the emergency first aid kit, the eye washing station and the shower station are located nearby, as shown in Figure 2-12.

---

### Table 2-2: Risk Assessment for Working in the Lab

#### 2.6.2 Working with the prototype

Identified Hazards: Injury from manufacturing prototype, including burn injury from soldering or hot wire and cuts from cutting plastics and wood.

Causes:
1) Inadequate PPE worn
2) Inexperience in soldering
3) Lack of concentration

**Risk Measure**: Medium Risk (Consequence: Minor, Likelihood: Possible)

Control Measures:
- Proper training in soldering should be provided. PPE such as safety glasses and gloves if needed to should be worn. Other personnel in the laboratory should keep a safe distance when manufacturing of prototype is in progress.
<table>
<thead>
<tr>
<th>Identified Hazards</th>
<th>Breathing irritation from solder fumes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Causes</td>
<td>(1) Inadequate ventilation</td>
</tr>
<tr>
<td></td>
<td>(2) Inexperience in soldering</td>
</tr>
<tr>
<td><strong>Risk Measure</strong></td>
<td><strong>Medium Risk</strong> (Consequence: Minor, Likelihood: Possible)</td>
</tr>
<tr>
<td>Control Measures</td>
<td>Proper training in soldering should be provided. Safety masks could be worn to avoid breathing in the fumes. Windows can be opened to allow air circulation. The soldering station has a solder fume extractor; therefore work should be done closer to the extractor.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Identified Hazards</th>
<th>Accidental swallowing and choking of device during trials</th>
</tr>
</thead>
<tbody>
<tr>
<td>Causes</td>
<td>Improper attachment to subject</td>
</tr>
<tr>
<td><strong>Risk Measure</strong></td>
<td><strong>Medium Risk</strong> (Consequence: Major, Likelihood: Unlikely)</td>
</tr>
<tr>
<td>Control Measures</td>
<td>Proper safe operating procedure and extreme care when attaching the device to the subject should be observed. Attachment of the device should be handled by professionals. After attaching the device, the subject should be asked to jump up and down to ensure the device is firmly attached to the patient.</td>
</tr>
</tbody>
</table>

**Table 2-3**: Risk Assessment for Working with the Prototype
3 Results and Discussion

3.1 Final Design

The final design uses two HESs and a magnet to calculate the jaw protrusion and jaw opening. Two differential amplifiers are used to amplify the output of the two HESs, and a 9V voltage regulator is used to regulate the input voltage to the system to avoid any damage to the system due to power surges. The outputs of the amplifiers are then read by the Arduino microcontroller, which then relays the amplified voltage to a computer with the computing software, Matlab® installed. Matlab® then calculates the jaw opening and jaw protrusion based on the amplified voltage. Figure 3-1 explains the operations of the system designed.

Figure 3-1: Block Diagram of Final System
The full bill of materials can be found in Appendix F. The two 2.2 kΩ resistors act as a voltage divider, providing 2.5V between the resistors. The 2.5 V is then provided to each of the amplifiers as the value in which the voltage outputs of the HESs were subtracted before being applied a gain.

Tamiya Epoxy Putty ® was chosen to encapsulate the two HESs, as it is easy to mould and form into the desired shape. It is a two-part epoxy, which by itself does not do anything, but when the two parts combined, the mixture will cure in 6 hours.

Figure 3-2 shows the final design of the amplifying circuit, which is built onto a stripboard. The outputs of the amplifiers are sent to the Arduino microcontroller.

![Figure 3-2: Final System Circuit Design](image)
3.2 Prototyping final design

The prototyping of the final design include building the HES system and building the amplifying circuit. Six strands of enamel wires that are stripped at the end are soldered onto the pins of the two HESs, and the strands are then connected onto a male 9-pin connector, which connects the HES system to the amplifying circuit. The main reason behind using 9-pin connectors is that it is easier to disassemble the circuit easily without needing to desolder anything from the amplifying circuit.

The two HESs which are connected by six strands of enamel wires are then places 8 mm apart. This 8 mm distance was measure by using a vernier calliper from the centres of the HESs. Tamiya Epoxy Putty ® is then used to encapsulate the two HESs. Extra care is taken to ensure that there are no sharp edges formed by the putty. It is vital that the putty covers over the solder joints; this is done to prevent the joints from Figure 3-3 shows the final design of the sensor system.

Figure 3-3: Final Design of Hall Effect Sensor System

Figure 3-4 shows the prototype developed based on the design in Figure 3-3. Some minor modifications were made, including minimizing the 5 mm height of the sensor system to
approximately 3 mm. This modification was made possible due to the moldability of the epoxy putty.

![Diagram of Prototype of Hall Effect Sensor System](image)

Figure 3-4: Prototype of Hall Effect Sensor System

The full procedure for building the prototype can be found in Appendix G. It details the procedure of building the circuit system and the sensor system.

3.3 Attaching to patients

At the current stage, the current system is only being tested on the experimental rig and the articulator, and no human trials are planned yet. At the moment, the current system is attached to the rig and the articulator by using Blu-Tack®, which is versatile, reusable putty-like adhesive. It is chosen to be used for experiment as it is easy to form into various shapes.

After consulting with Dr. Christopher Pantin from Absolute Dental, it is decided that using Filtek™ Z250 Universal Dental Restorative, light cured composite resin would be a possible candidate for attaching the system onto a patient’s teeth. This procedure is not needed at the current stage, as the system is still under development.
Figure 3-5 shows how the sensor system and the magnet are placed on the articulator, which simulates how the system will be placed on the human teeth. Note that the sensor system is placed on the maxilla and the magnet is placed on the mandible.

![Diagram of sensor system and magnet on articulator]

**Figure 3-5:** (a) Hall Effect Sensor System attached to the articulator, (b) Boxed area magnified

### 3.4 Microcontroller

At the current stage, the Arduino microcontroller reads the voltage outputs of each sensor from 0V to 5V, and converts those voltages to Analog-To-Digital Converter (ADC) values from 0 to 1023, with each unit representing approximately 5mV. These values are then sent to a computer with Matlab® installed by using a Universal Serial Bus (USB) cable. The Matlab® code which was written concurrently will then determine the distances between the sensors and the magnet. The code for the Arduino, HESReadDigital.pde can be found in Appendix H.
3.5 Matlab® Code

There are two parts to the Matlab® code: before testing and during testing. The before testing is also called the calibration test, where the HES outputs when the magnet is directly in front of each sensor are collected. The outputs are then entered into the Matlab® code, where two lookup tables were constructed, one for each sensor. The lookup tables enable the second part of the code to look for the corresponding distances between each sensor and the magnet given the voltage outputs of the sensors. The lookup tables are constructed by interpolating between the data points collected in the calibration test, so that every possible output from the microcontroller corresponds to a distance between the sensor and the magnet. Details on the calibration test can be found in the next section.

The second part of the Matlab® code obtains the voltage outputs from the microcontroller, and converts the voltage outputs to the distances between each sensor and the magnet. The distances are then analysed, and the jaw opening and jaw protrusion direction are calculated. Figure 3-6 describes the roles the Matlab® code played in the design.

(a) Before testing

Initial calibration of Hall Effect Sensors

Process and interpolate data between intervals

Construct Lookup Table for each Hall Effect Sensors

(b) During testing

Obtain voltage outputs from microcontroller

Convert voltage outputs to distances

Calculate jaw opening and jaw protrusion

Figure 3-6: Block Diagram of Matlab® Code
The full version for the code can be found in Appendix I, where the codes are divided into different files: arduinoToMatlab.m, readVoltage.m, calculateData.m, interpolateData.m and finalProject.m. Descriptions for each of the codes are also provided.

3.6 Calibration Test on Final Design

A calibration test is performed on the final design to get the voltage outputs of the sensors in relation to the distance between the sensors and magnet. The calibration test is carried out by increasing the distance between the sensors and the magnet by 1 mm intervals for the first 55 mm, and by 5 mm intervals up till 90 mm. At the current stage, the voltage outputs are collected by using two identical multimeters. The relationship is then represented in Figure 3-7. The calibration data can be found in Appendix J.

![Output Voltages for Each Sensors Collected](image)

**Figure 3-7:** Sensor Voltage Output versus Distance between Sensor and Magnet

After obtaining the data in Figure 3-7, it is then sent to the first part of the Matlab® code. The code then converts the voltage outputs to an ADC value in the range of 0 - 1023, with each ADC value representing 5 mV. The code then interpolates the data linearly between the intervals to get the corresponding distances, so that each ADC value between the minimum ADC value and the maximum ADC value has a corresponding distance. The
interpolated data is then placed in a lookup table to facilitate the second part. Figure 3-8 represents interpolated ADC values and the corresponding distances.

![Figure 3-8: Interpolated Analog-To-Digital Values and the corresponding distances](image)

3.7 Data Collected

The definitions of measured X and measured Y can be seen in Figure 3-9. Note that the initial position stands for the position where the magnet is directly in front of the middle point between the two sensors and 5 mm away from the sensor system. All the data collected can be found in Appendix L.

![Figure 3-9: Definition of (a) Measured X and (b) Measured Y](image)
The calculated Y values produced by the Matlab® program are compared with the measured Y values in Figure 3-10.

![Calculated Y vs Measured Y](image)

**Figure 3-10:** Calculated Y versus Measured Y

The calculated Y values are relatively close to the expected values, and this is promising. By drawing a coefficient of determination ($R^2$) line by using Microsoft Excel, a $R^2$ value of 0.9565 is obtained. This shows that the Matlab® code is able to calculate the displacement in the Y direction with relatively high certainty.

Table 3-1 summarised the average of the calculated Y values and shows the average deviation from the expected value.

<table>
<thead>
<tr>
<th>Measured Y Values (mm)</th>
<th>Average of Calculated Y Values (mm)</th>
<th>Difference between Average Calculated Y Values and Measured Y Values (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>5.68</td>
<td>+0.68</td>
</tr>
<tr>
<td>10</td>
<td>9.20</td>
<td>-0.80</td>
</tr>
<tr>
<td>15</td>
<td>15.21</td>
<td>+0.21</td>
</tr>
<tr>
<td>20</td>
<td>20.36</td>
<td>+0.36</td>
</tr>
<tr>
<td>25</td>
<td>26.08</td>
<td>+1.08</td>
</tr>
<tr>
<td>30</td>
<td>31.22</td>
<td>+1.22</td>
</tr>
</tbody>
</table>

**Table 3-1:** Analysis of Calculated Y values (Jaw Opening)
It is observed that the average calculated Y values are close to the expected Y values, with the maximum deviation of 1.22 mm. Since the experiment started with an initial Y value as 5 mm, as this is the separation desired between the sensor system and the magnet, it is concluded that the system proposed is able to detect jaw opening for distances up to 25 mm.

The calculated X values produced by the Matlab® program is compared with the measured X values in Figure 3-11.

![Figure 3-11: Measured X versus Calculated X](image)

It can be observed that there is much difference between the measured X values and the calculated X values. Although so, there is an observable trend in the scattering of values. Thus, a polynomial curve of order 3 was fitted onto the scattered values, and an equation was obtained.

The calculated X values obtained from Matlab® is then inserted into the fitted equation, and the outputs of the equation, fitted X values, are shown in Figure 3-12 in comparison with the measured X values.
The fitted X values are relatively close to the expected X values, and that is expected as these are values from the fitted curve. By drawing a coefficient of determination (R²) line by using Microsoft Excel, a R² value of 0.957 is obtained.

<table>
<thead>
<tr>
<th>Measured X Values (mm)</th>
<th>Average of Fitted X Values (mm)</th>
<th>Difference between Average Fitted X Values and Measured X Values (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>-3</td>
<td>-2.98</td>
<td>+0.02</td>
</tr>
<tr>
<td>-2</td>
<td>-1.83</td>
<td>+0.17</td>
</tr>
<tr>
<td>-1</td>
<td>-0.87</td>
<td>+0.13</td>
</tr>
<tr>
<td>0</td>
<td>-0.13</td>
<td>-0.13</td>
</tr>
<tr>
<td>1</td>
<td>0.79</td>
<td>-0.21</td>
</tr>
<tr>
<td>2</td>
<td>2.15</td>
<td>0.15</td>
</tr>
<tr>
<td>3</td>
<td>2.86</td>
<td>-0.14</td>
</tr>
</tbody>
</table>

**Table 3-2:** Analysis of Fitted X values (Jaw Protrusion)

It is observed in Table 3-2 that the average fitted X values are close to the expected X values, with a maximum deviation of 0.21 mm. This shows that for applying the calculated X values obtained from Matlab® to the equation, a reasonable estimate of the expected X values can be obtained.
3.8 Further Discussion

3.8.1 Comparison to original expectations

At the beginning of the project, it was assumed that the voltage outputs of the sensors would be the same, given the same conditions. This is not the case, as the HESs selected are mass produced, and with that, there will be discrepancies between any two HESs. Therefore an additional step for calibrating the two HESs was added to the testing process.

Another assumption that was made during the start of the project was that the voltage output of a HES was proportional with distance between the sensor and the magnet. During the duration of the project, it was discovered that was not the case, as there are various variables that need to be considered.

The system that was developed in this project aimed to measure both the jaw opening and the jaw protrusion. This system was successful in measuring that, albeit with some margin of error. The measurement of the jaw opening proved to be quite accurate, with the maximum deviation from the expected value as 1.22 mm for average calculated jaw opening.

On the other hand, the calculation for the jaw protrusion yielded poor results, as the differences between the measured and calculated distances were too big. Even so, the calculated data for the jaw protrusion does exhibit a trend, and by fitting a polynomial curve of order 3 and applying calculated data for the jaw protrusion to the fitted equation, fitted data for the jaw protrusion are able to predict the expected jaw protrusion. The average of the fitted data for the jaw protrusion provides a reasonable estimate, with a maximum deviation from the expected value as 0.21 mm for average calculated jaw opening.

3.8.2 Comparison to pre-existing state of art

The systems that were investigated in the literature review which were of a similar dimension and were using magnetic sensors were only able to detect jaw movement in only one direction (Flavel, Nordstrom & Miles 2003) (Deich, Allan & Zeigler 1984)
(Miyamoto et al. 1998) (Akamatsu, Minagi & Sato 1996). The final system proposed in this project is able to measure both jaw opening and jaw protrusion. In addition to that, this system has the advantage of having a larger range in detecting jaw protrusion (Akamatsu, Minagi & Sato 1996), and it is also able to match the range for jaw opening by other similar systems (Flavel, Nordstrom & Miles 2003) (Miyamoto et al. 1998).

The performance of this system paled in comparison with other systems which uses magnetic sensors to detect jaw movement in multiple directions (Dove et al. 1994) (Yabukami et al. 2003). Although so, the other systems required the subject to be fixed in stationary, and this does not fit the criteria for this project, as it is established that the subject should be able to change his sleeping position at will without interfering with the data collection. In addition to that, those other systems are too bulky and expensive to operate.

The final design was modified from the system proposed by Miyamoto and his team (Miyamoto et al. 1998). By adding an additional HES, the final design is able to detect both jaw opening and jaw protrusion.

3.8.3 Comparison to alternative approach

An alternative approach of using three HESs was considered. The reason behind adding another HES was to detect lateral jaw movement, which is the mandible moving sideways, alongside other jaw movements. This approach was discarded as it was deemed to be too time consuming, and it is also out of the scope of the project. Although so, this implementation can be considered in a future project.

3.8.4 Limitations

Since the calibration of the sensor system is only done up to 90 mm, the distance between the magnet and the sensor can’t exceed 90 mm. As the jaw opens or protrudes, the distances between the magnet and the sensors will increase. In the calibration test, as the distance between the sensor and the magnet increases, the voltage output becomes
indiscernible compared to the previous distance. This will cause the calculation governed by the equations discussed from Equations (2.2) to (2.9) to produce unexplainable data. In order to fix this problem, a stronger magnet, more sensitive HESs or additional amplifiers with a higher gain can be used to detect voltage changes in large distances.
4 Conclusions and Future Work

4.1 Conclusion

The original objectives of this project were:

- to design, build and test a system to measure jaw movement
- to develop a computer model to calculate the jaw opening and jaw protrusion
- and to integrate with the data logger system at WASDRI.

The first objective was achieved by the development and fabrication of a system which utilised two SS495A1 HESs encapsulated in Tamiya ® epoxy putty and one disc-sized magnet with a diameter of 10 mm and a thickness of 3 mm to measure both jaw opening and jaw protrusion. The sensors and magnet will be attached to the maxilla and mandible of the patient respectively. The second objective was achieved by the development of the code in Matlab®, which was able to calculate the jaw protrusion and jaw movement if provided the voltage outputs from the HESs. An Arduino microcontroller serves as a bridge, transmitting the voltage outputs of the Hall Effect Sensors into Matlab®. Unfortunately, the third objective was unable to be achieved and would be explained on the next page.

A prototype of the final system was designed and fabricated. The fabrication method was detailed in this report for future references. The shape and size of the prototype can be modified due to the moldability of the epoxy putty before it was fully cured. Preliminary testing on the fabricated prototype of the final system was done on a custom built experiment rig, and the data collected confirmed the validity of the assumption made at the start of the project. The assumption was by using two HESs, both jaw opening and jaw protrusion can be calculated.

This project is part of a multi-year project, which aims to measure the upper body position of a sleep apnoea patient, and the objectives outlined at the start of the project were fulfilled. Several delays such as attempting to interface the HES system with the microcontroller and Matlab® hindered the progress of the project slightly, but in the end, the project was able to progress at a steady state.
4.2 Future Work

Live human trials are planned at the interstate and international level, which requires the system to not only be compatible with systems used in SCGH, but also in hospital across the world. Problems such as language barriers and the reliability for the system will need to be looked into, as at the current stage, it is impossible to fix the system remotely.

In addition to that, integration with the data logger at WASDRI will need to be done. This can be achieved by relaying the calculated jaw opening and jaw protrusion from the Matlab® code back to the Arduino microcontroller. The Arduino microcontroller can then relay these values into a TLV5608 Digital-to-Analog Converter (DAC) (Crocker 2010). The DAC can then transfer the values to the data logger in the sleep clinic, and be displayed on the user interface.

The addition of a third HES will enable the detection of lateral jaw movement, which is the movement where the mandible moves sideways. The 3 HESs will act like a miniaturized Global Positioning System (GPS). By using 3 HESs concurrently, the mandible movement can be detected in three different directions, thus providing more valuable data to the researchers. This was out of the scope of the project for this year, and the placement and selection of the sensors and the magnet will need to be investigated further.

The addition of a wireless interface will greatly reduce the clutter and the risk of strangulation of a patient. However, all the surrounding equipments in the sleep clinic and the corresponding noise will provide a challenge in introducing a wireless interface. The means to power a wireless system will also be a challenge, as it would require attaching batteries to the patient directly, keeping in mind that the proposed system is an intra-oral system. Bluetooth modules can be considered as a means of collecting data, and this would make for an interesting and challenging future project.

The accuracy and range of detection for the sensor system can be improved further by searching for sensors that are more sensitive and magnets with a stronger magnetic field. Additional amplifiers with larger gains can also be added to the system to amplify the voltage outputs of the system, so that larger distances can be detected by the sensors. Other
systems, such as the Inertial Measurement Unit system (Lin et al. 2010a; Lin et al. 2010b) can also be investigated.

To summarise, this project has laid a foundation for further research, design and fabrication of a device for measuring jaw movement. Future works such as improving the current design, development of a wireless system, integration with the data logger at WASDRI and investigation of other systems are also proposed.
5 References


Crocker, M 2010, 'Measuring head, mandible and body posture changes during sleep', School of Mechanical and Chemical Engenieng, University of Western Australia.


Fry, O 2011, 'Measuring Upper Body Position in Sleep Apnoea Patients', School of Mechanical and Chemical Engineering, University of Western Australia.


Appendix A – Calculation for Different Scenarios

Scenario 1: When angle $\alpha$ and angle $\beta \leq 90^\circ$

If $d_1 > d_2$

$$\alpha = \arccos\left(\frac{d^2 + d_1^2 - d_2^2}{2d_1d}\right)$$

$$\beta = \arcsin\left(\frac{d_1 \cdot \sin(\alpha)}{d_2}\right)$$

If $d_2 > d_1$

$$\beta = \arccos\left(\frac{d^2 + d_2^2 - d_1^2}{2d_2d}\right)$$

$$\alpha = \arcsin\left(\frac{d_2 \cdot \sin(\beta)}{d_1}\right)$$

$$x_1 = d_1 \cdot \cos(\alpha) - \frac{d}{2}$$

$$x_2 = \frac{d}{2} - d_2 \cdot \cos(\beta)$$

$$y_1 = d_1 \cdot \sin(\alpha)$$

$$y_2 = d_2 \cdot \sin(\beta)$$

$$x = \frac{x_1 + x_2}{2}$$

$$y = \frac{y_1 + y_2}{2}$$
Scenario 2: When angle $\alpha \leq 90^\circ$ and angle $\beta \geq 90^\circ$

\[\alpha = \arccos \left( \frac{d^2 + d_1^2 - d_2^2}{2 \cdot d \cdot d_1} \right) \quad \text{(B.9)}\]

\[\beta = \arcsin \left( \frac{d_1 \cdot \sin(\alpha)}{d_2} \right) \quad \text{(B.10)}\]

\[x_1 = d_1 \cdot \cos(\alpha) \quad \text{(B.11)}\]

\[x_2 = d_2 \cdot \cos\left(180^\circ - \beta\right) \quad \text{(B.12)}\]

\[y_1 = d_1 \cdot \sin(\alpha) \quad \text{(B.13)}\]

\[y_2 = d_2 \cdot \sin\left(180^\circ - \beta\right) \quad \text{(B.14)}\]

\[x = \frac{(x_1 - \frac{d_1}{2}) + (x_2 + \frac{d_2}{2})}{2} = \frac{x_1 + x_2}{2} \quad \text{(B.15)}\]

\[y = \frac{y_1 + y_2}{2} \quad \text{(B.16)}\]
Scenario 3: When angle $\alpha \geq 90^\circ$ and angle $\beta \leq 90^\circ$

\[
\beta = \arccos \left( \frac{d^2 + d_2^2 - d_1^2}{2d \cdot d_2} \right) \tag{B.17}
\]

\[
\alpha = \arcsin \left( \frac{d_2 \cdot \sin(\beta)}{d_1} \right) \tag{B.18}
\]

\[
x_1 = d_1 \cdot \cos(180^\circ - \alpha) \tag{B.19}
\]

\[
x_2 = d_2 \cdot \cos(\beta) \tag{B.20}
\]

\[
y_1 = d_1 \cdot \sin(180^\circ - \alpha) \tag{B.21}
\]

\[
y_2 = d_2 \cdot \sin(\beta) \tag{B.22}
\]

\[
x = -\frac{(x_1 + \frac{d}{2}) + (x_2 - \frac{d}{2})}{2} = -\frac{(x_1 + x_2)}{2} \tag{B.23}
\]

\[
y = \frac{y_1 + y_2}{2} \tag{B.24}
\]
Appendix B – Procedure for Constructing Articulator

Part A – Set up
1) Clean up the articulator, so that there are no foreign substances attached on the articulator
2) Disassemble mounting pads from the articulator in order to attach the teeth models onto the mounting pads
3) Clean up the smooth part of the teeth models

Part B – Prepare plaster of Paris
1) Measure the amount of plaster of Paris powder needed to attach the teeth models onto the mounting pads.
2) Measure the water needed to mix with the powder. The amount of water needed is equivalent to three times the amount of the powder.
3) Add the water into a large container.
4) Add the powder slowly into the container, spreading it across the surface of the water in order to prevent the powder to form lumps. Stir constantly.
5) Once all the powder was added to the water, the mixture should resemble putty. If the mixture is still too runny, let it set for a little longer.

Part C – Attach teeth model
1) At this point, the teeth models should be prepared and the plaster of Paris mixture should be mixed properly.
2) Place the mixture on the mounting plate.
3) Place the teeth model on top of the mixture. It is vital for the mixture to resemble putty and not too runny. Otherwise, the teeth model will simply sink into the mixture.
4) Carve away the excess mixture.
5) Repeat step (2) to step (4) for the other mounting plate.
6) Leave the mounting plates in an open space to dry for approximately 30 minutes.
7) The mixture should have hardened up, and the teeth model should be attached to the mounting pad firmly.
8) Reattach the mounting plate onto the articulator.
Appendix C – Safe Operating Procedure for Soldering

Preparation for solder:
1) Clear the workbench and ensure there is enough space to put the soldering iron station, bracket and sponge
2) Switch on the soldering iron station, and wait for approximately 1 minute for the soldering iron to warm up.
3) Coat the entire soldering iron’s tip with a thin coat of solder. Run the solder up and down the soldering iron’s tip to ensure it is fully coated in molten solder.
4) Clean the soldering tip on a wet sponge. Do this immediately to prevent the flux residue from drying and solidifying on the soldering iron’s tip’s surface.

Soldering on a stripboard
1) Record down where each components of the circuit will go onto the board. Keep in mind each long strip on the board is conductive.
2) Place the components onto the board. Bend the leads as necessary and insert the components through the proper holes on the board. In order to ensure the component stay in place when soldering, bend the component’s lead at 45 degree angle, so that it does not slip out of the hole.
3) Apply small amount of solder on the tip of the soldering iron. Heat the joint by laying the tip of the iron so that it rests against both the component lead and the board. It takes one or two seconds for the joint to heat up.
4) Take a strand of solder and touch the joint, but not the tip of the iron. Pay attention to the amount of solder applied on the joint. If it starts to ball up, it means too much solder has been applied.
5) Once the joint is fully coated, stop adding solder and remove the soldering iron.

Soldering wires to Hall Effect Sensor pins
1) Strip the enamel wire properly, so that there is no coating left on the tip of the enamel wires.
2) Apply heat on the wire by touching the tip of the wire for a second or two.
3) Once the wire is hot enough, apply some solder on the tip of the wire.
4) Apply small amount of solder on the Hall Effect Sensor pin as well.
5) After the wire and the pin have cooled, align the wire and the pin end to end, and solder the two together, feeding extra solder if needed.

6) After the solder has cooled down and solidified, check the joint. If the joint wobbles, repeat step 2 to 5.

Caution

1) Do not touch the soldering iron’s tip in any circumstances.

2) Remember to clean the soldering iron’s tip after every use.

3) Do not apply heat on the Hall Effect Sensor pins for too long, as the Hall Effect Sensor will become faulty. The same applies for the components of the circuit.
Appendix D – Safety Induction

School of Mechanical and Chemical Engineering
Student Project Safety Induction

| Student’s Name: | Wilfred Wong (10759594) |
| Supervisor: | Professor Adrian Keating |
| Relevant Labs: | G55 |
| Keys Issued: | Yes |

This safety induction permits the inductee to access the specified laboratories or work areas and to carry out the assigned tasks without supervision.

<table>
<thead>
<tr>
<th>Project Outline and Safety Review</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Project Title:</strong> Measuring upper body position during sleep in sleep apnoea patients</td>
</tr>
</tbody>
</table>

**Project Details:**
1) Develop and implement a system utilizing Inertial Measurement Units to measure upper body orientation during sleep
2) Develop and implement a system utilizing Hall Effect Sensors and a magnet to measure jaw movements during sleep

**List of Hazards:**
1) Manual Handling
2) Competency with hand tools
3) Electrical connections (spark and fire hazards), only allowed to use low voltages (5V)
4) Fire and Emergency evacuation
5) Working alone or outside normal working hours
6) Using chemicals to build printed circuit boards

**Induction and Training:** Provided for each of the identified hazards

**Safety Requirements:**
1) Safety glasses
2) Closed shoes

The undersigned student has received and understood all the necessary information, instruction and training to carry out the allocated task safely. The project has been properly assessed by the supervisor for compliance with all School and UWA procedures and legal responsibilities. Where significant risks have been identified, a written Risk Assessment Report has been completed and approved. Any changes to the work method or deviation from procedure will be brought to the supervisor’s attention.

Project Supervisor’s Signature…………………………………………Date…………..

Area Supervisor’s Signature…………………………………………Date…………..

Student’s Signature……………………………………………………Date…………..
Appendix E – Emergency Contacts & Risk Measures Categorization

UWA’s Emergency Contacts

<table>
<thead>
<tr>
<th>24 hrs Emergency Contact</th>
<th>6488 2222</th>
</tr>
</thead>
<tbody>
<tr>
<td>Medical Centre</td>
<td>6488 2118</td>
</tr>
<tr>
<td>Electrician Technical Officer</td>
<td>6488 2036</td>
</tr>
<tr>
<td>Counselling</td>
<td>6488 2423</td>
</tr>
<tr>
<td>Safety and Health</td>
<td>6488 3938</td>
</tr>
</tbody>
</table>

Risk Rating Table

<table>
<thead>
<tr>
<th>Likelihood Consequences</th>
<th>Rare E</th>
<th>Unlikely D</th>
<th>Possible C</th>
<th>Likely B</th>
<th>Almost Certain A</th>
</tr>
</thead>
<tbody>
<tr>
<td>5 Catastrophic</td>
<td>Medium</td>
<td>Medium</td>
<td>High</td>
<td>Extreme</td>
<td>Extreme</td>
</tr>
<tr>
<td>4 Major</td>
<td>Low</td>
<td>Medium</td>
<td>High</td>
<td>High</td>
<td>Extreme</td>
</tr>
<tr>
<td>3 Moderate</td>
<td>Low</td>
<td>Medium</td>
<td>Medium</td>
<td>High</td>
<td>High</td>
</tr>
<tr>
<td>2 Minor</td>
<td>Low</td>
<td>Low</td>
<td>Medium</td>
<td>Medium</td>
<td>Medium</td>
</tr>
<tr>
<td>1 Insignificant</td>
<td>Low</td>
<td>Low</td>
<td>Low</td>
<td>Low</td>
<td>Medium</td>
</tr>
</tbody>
</table>
Consequences Table – Health and Safety:

<table>
<thead>
<tr>
<th>Consequence Rating</th>
<th>What it stands for</th>
</tr>
</thead>
<tbody>
<tr>
<td>5 Catastrophic</td>
<td>Death of staff, contractor, student or member of public</td>
</tr>
<tr>
<td>4 Major</td>
<td>Serious injury or occupational illness or permanent major disabilities</td>
</tr>
<tr>
<td>3 Moderate</td>
<td>Loss time or restricted injury or occupational illness</td>
</tr>
<tr>
<td>2 Minor</td>
<td>Medical treatment or first aid injury no lost time or occupational illness</td>
</tr>
<tr>
<td>1 Insignificant</td>
<td>No injury or occupational illness</td>
</tr>
</tbody>
</table>

Likelihood Table

<table>
<thead>
<tr>
<th>Likelihood Rating</th>
<th>What it stands for</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rare E</td>
<td>Very low, very unlikely during the next twenty-five years</td>
</tr>
<tr>
<td>Unlikely D</td>
<td>Not impossible, likely to occur during the next ten to twenty-five years</td>
</tr>
<tr>
<td>Possible C</td>
<td>Possible, may arise at least once in a one to ten year period</td>
</tr>
<tr>
<td>Likely B</td>
<td>High, may arise about once per year</td>
</tr>
<tr>
<td>Almost Certain A</td>
<td>Very high, may occur at least several times per year</td>
</tr>
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</table>
### Appendix F – Bill of Materials

<table>
<thead>
<tr>
<th>Name</th>
<th>Extra Description</th>
<th>Serial Number</th>
<th>Place to Obtain</th>
<th>Quantity</th>
<th>Cost per unit (AUD)</th>
<th>Cost (AUD)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Amplifier</td>
<td>Quad Operational Amplifier</td>
<td>LM324</td>
<td>Jaycar Electronics</td>
<td>1</td>
<td>1.95</td>
<td>1.95</td>
</tr>
<tr>
<td>Battery</td>
<td>Eclipse 9V Alkaline Battery</td>
<td>-</td>
<td>Jaycar Electronics</td>
<td>1</td>
<td>3.95</td>
<td>3.95</td>
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<tr>
<td>Epoxy Putty</td>
<td>Tamiya Epoxy Putty</td>
<td>-</td>
<td>Stanbridges, Australia</td>
<td>1</td>
<td>9.95</td>
<td>9.95</td>
</tr>
<tr>
<td>Hall Effect Sensor</td>
<td></td>
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<td>RS Online Australia</td>
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Appendix G – Prototype Building

Equipments and components needed

1) Soldering iron
2) Lead-free solder
3) Two SS495A1 Hall Effect Sensors
4) One disc-sized magnet with diameter of 10 mm and thickness of 3 mm
5) Tamiya® two-part epoxy putty
6) Length measuring device, such as ruler or vernier calliper
7) A piece of plastic
8) 6 strands of enamel wires
9) Resistors with different values
10) Quad operational amplifier LM324
11) Wires of different length
12) Stripboard
13) Drill bit
14) 14-pin IC socket
15) Male and female 9-pin connectors

Procedure for building prototype:

Circuit system

1) Design the Stripboard circuit based on the schematic diagram presented in Figure 3-2.
2) Build the circuit based on the design on a Stripboard (See Appendix C for safe operating procedure for soldering)
3) For the amplifier, mount the IC Socket before mounting the amplifier. Use the drill bit to strip away the copper between the pins of the socket.
4) Connect a male 9-pin connector to the circuit system.

Hall Effect Sensor system

1) Solder enamel wires to the pins of the two Hall Effect Sensors. (See Appendix C)
2) Place the two sensors 8 mm apart, measured from the centres of the sensors.
3) Mix equal amount of both parts of the epoxy putty, until the mixture is the same colour throughout.
4) Encapsulate the mixture around the Hall Effect Sensors, and mould it to the desired shape and size.

5) Wait for the epoxy putty to cure, which takes around 6 to 8 hours.

6) Once the epoxy putty is cured, solder the other end of the enamel wires onto a female 9-pin connector. Note the pins match the pin configuration of the male 9-pin connector.

**Combining the two systems**

1) Connected the two systems by connecting the 9-pin connectors.

2) Attach the wires relaying the amplified voltage outputs onto the Arduino microcontroller

3) Use a USB cable to connect the Arduino microcontroller to the computer

4) Upload the Arduino code to the Arduino microcontroller

5) Run Matlab® code, which then displays the calculated X (jaw protrusion) and Y (jaw opening) values.
Appendix H – Arduino Code

/*
 HESReadDigital
 Reads a outputs for 2 Hall Effect sensors,
 prints the result to the serial port,
 and read by Matlab
 */

// Declaration of global variables

// Hall Effect Sensor Variables
const int pinHES1 = A1; // Set Analog Pin 1 as the pin which reads the output from Hall Effect Sensor 1
const int pinHES2 = A2; // Set Analog Pin 2 as the pin which reads the output from Hall Effect sensor 2

int sensorValue1 = 0; // Initialize sensorValue1 as 0
int sensorValue2 = 0; // Initialize sensorValue2 as 0

void setup(){
  Serial.begin(9600); // Pulse per second, at the moment, default it as 9600
}

void loop(){
  sensorValue1 = analogRead(pinHES1); // Read voltage output from Hall Effect Sensor 1
  sensorValue2 = analogRead(pinHES2); // Read voltage output from Hall Effect Sensor 2
  Serial.print(sensorValue1,DEC); // Print the output from sensor 1 onto the serial port as a value from 0 to 1023
  Serial.print("\t"); // Place a tab between the two sensor outputs
  Serial.print(sensorValue2,DEC); // Print the output from sensor 2 onto the serial port as a value from 0 to 1023
  Serial.println();
  Serial.flush();
}
Appendix I – Matlab Code

% --------------------------------------------------
% arduinoToMatlab.m                                  %
% Reads the amplified voltages of the Hall Effect    %
% Sensors and calculate the jaw opening and jaw     %
% protrusion                                         %
% --------------------------------------------------

% Written by Wilfred Wong
% Received help from Jason Cippitelli

clear everything, including closing open ports
clc
disp('Closing open ports... Please wait');
clear all;
close all;

% Read and delete serial port objects from memory
oldSerial = instrfind();
delete(oldSerial);

% Declare serial port as COM4, or other COM, provided it is
% the same as the
% Arduino microcontroller
s1 = serial('COM4');
s1.BaudRate = 9600; %set Baud rate the same as the rate in
HESReadDigital.pde

% Get the new serial port object
newobjs = instrfind;

% Open port
fopen(s1);
clear data;

% Read the voltage using helper function readVoltage(s1), to
read from the
% serial port
SerialCMD = '';
fprintf(s1,'%s',SerialCMD);
data = readVoltage(s1);

% Get V1 and V2 separated by spaces
V1 = data(1);
V2 = data(2);

% For debugging purposes, to see what V1 and V2 are
fprintf('V1 = %d
',V1);
% fprintf('V2 = %i\n',V2);

% Call another helper function to calculate jaw opening and jaw protrusion
[x,y] = finalProject(V1,V2);
% Print them out on the Matlab command window
fprintf('x = %d\n',x);
fprintf('y = %d\n',y);

% Close and delete everything
fclose(s1)
delete(s1)
newSerial = instrfind();
delete(newSerial)
clear s1;
clear newSerial;
% readVoltage.m
% Read voltages from serial port
% The voltages are separated by a space

% Variable:
% s1 - com port to scan for voltage data

% Output:
% DataBack - voltage from two Hall Effect Sensors in an array, separated by
% from a single string, which is separated by a space

% Written by: Wilfred Wong
% Received help from Jason Cippitelli

function DataBack=readVoltage(s1)
    SerialCMD = '';
    fprintf(s1,'%s',SerialCMD);
    data=fscanf(s1);   %scan data from serial port

    temp_string = data;
    fprintf(temp_string);
    a = find(isspace(temp_string));
    V1 = str2double(temp_string(1:a(1)-1));
    V2 = str2double(temp_string(a(1)+1:a(2)-1));
    DataBack=[V1,V2];
end
% finalProject.m
% Stand alone function, as it can be used to debug the system.
% Calculate the jaw opening and jaw protrusion
%------------------------------------------

% Variables:
% testV1Arduino: ADC values from Arduino for Hall Effect Sensor 1, from 0-1023
% testV2Arduino: ADC values from Arduino for Hall Effect Sensor 2, from 0-1023

% Output:
% x: jaw protrusion
% y: jaw opening

% Written by: Wilfred Wong

function [x,y] = finalProject(testV1Arduino,testV2Arduino)
    % Data collected during calibration test
    % airGap is the distance between the sensor and the magnet
    airGap = [8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23
              24 25 26 27 28 29 30 31 32 33 34 35 36 37 38 39 40 41 42 43
              44 45 46 47 48 49 50 51 52 53 54 55 60 65 70 75 80 85 90];
    % minus 5 for the initial distance. This allows for better interpolation. The initial distance will be added back in the calculation for displacement
    airGap = airGap - 5;
    % voltage for sensor 1
    v1 = [3.71 3.29 2.77 2.38 2.09 1.87 1.7 1.571 1.468 1.383 1.313 1.256 1.209 1.171 1.138 1.11 1.087 1.069 1.052 1.038 1.025 1.014 1.004 0.996 0.988 0.981 0.975 0.97 0.965 0.961 0.957 0.953 0.95 0.947 0.944 0.942 0.94 0.938 0.936 0.935 0.933 0.932 0.931 0.93 0.929 0.928 0.927 0.926 0.923 0.92 0.919 0.917 0.916 0.915 0.914];
    % voltage for sensor 2
    % Use helper function interpolateData to interpolate between intervals,
% so that there is a corresponding distance for every ADC values
[newV1,newX1,newV2,newX2] = interpolateData(airGap,v1,v2);
% Get the boundaries for each sensors
lowestV1 = newV1(numel(newV1));
lowestV2 = newV2(numel(newV2));
highestV1 = newV1(1);
highestV2 = newV2(1);

if (testV1Arduino < lowestV1)
    testV1Arduino = lowestV1;
end
if (testV1Arduino > highestV1)
    testV1Arduino = highestV1;
end
if (testV2Arduino < lowestV2)
    testV2Arduino = lowestV2;
end
if (testV2Arduino > highestV2)
    testV2Arduino = highestV2;
end

% Use helper function calculateData to calculate the jaw opening and jaw protrusion
[x,y] =
calculateData(newV1,newX1,newV2,newX2,testV1Arduino,testV2Arduino);
end
% interpolateData(x,v1,v2) % Find a corresponding distance for every ADC values by using linear interpolation between intervals % % Variables:
% x - Distance between the sensor and the magnet
% v1 - Voltage output of sensor 1
% v2 - Voltage output of sensor 2

% Outputs:
% newV1 - An array of ADC values for sensor 1 which corresponds to newX1
% newX1 - An array of distances which corresponds to newV1
% newV2 - An array of ADC values for sensor 2 which corresponds to newX2
% newX2 - An array of distances which corresponds to newV2

% Written by: Wilfred Wong

function [newV1,newX1,newV2,newX2] = interpolateData(x,v1,v2)

% Ensure that each the voltage can be represented in 5 mV intervals
v1 = floor(v1/5*1024);
v2 = floor(v2/5*1024);

% Get the size of initial array
[u,v] = size(x);

% Initialise empty array to store values
newX1 = [];
newX2 = [];
newV1 = [];
newV2 = [];

% Interpolate for every ADC values, so that there is a corresponding distance for every ADC values. The interpolation is done linearly.
for n = 1:1:v-1
    aV1 = x(n+1) - x(n);
    bV1 = v1(n) - v1(n+1);
    incrementX1 = aV1/bV1;

    aV2 = x(n+1) - x(n);
    bV2 = v2(n) - v2(n+1);
    incrementX2 = aV2/bV2;

    % Interpolate for newX1
    newX1 = newX1 + incrementX1;

    % Interpolate for newX2
    newX2 = newX2 + incrementX2;

    % Collect the ADC values
    newV1 = [newV1,v1(n+1)];
    newV2 = [newV2,v2(n+1)];
end
partX1 = x(n):incrementX1:x(n+1);
newX1 = [newX1 partX1];
partV1 = v1(n):-1:v1(n+1);
newV1 = [newV1 partV1];

partX2 = x(n):incrementX2:x(n+1);
newX2 = [newX2 partX2];
partV2 = v2(n):-1:v2(n+1);
newV2 = [newV2 partV2];
end
end
% calculateData.m                                   
% Helper function for calculation the jaw opening and jaw protrusion based on the two voltages provided. 
% Due to time constraint, only Scenario 1 detailed in Appendix B was implemented 

-------

% Inputs: 
% newV1: An array of ADC values for sensor 1 
% newX1: An array of distances which corresponds to newV1 
% newV2: An array of ADC values for sensor 2 
% newX2: An array of distances which corresponds to newV2 
% V1: The ADC values from Arduino microcontroller for sensor 1 
% V2: The ADC values from Arduino microcontroller for sensor 2 

% Outputs: 
% x: Displacement in the x direction, which represents the jaw protrusion 
% y: Displacement in the y direction, which represents the jaw opening 

function [x,y] = calculateData(newV1,newX1,newV2,newX2, V1, V2) 

% Get the distance when ADC value for sensor 1 is V1 
% Get the distance when ADC value for sensor 2 is V2 

% Default distance between sensors 

d = 8;
% Calculation of angles alpha and beta
if (newd1 > newd2)
    beta = acos((newd2^2 + d^2 - newd1^2)/(2*newd2*d));
    alpha = asin((newd2*sin(beta))/newd1);
else
    alpha = acos((newd1^2 + d^2 - newd2^2)/(2*d*newd1));
    beta = asin((newd1*sin(alpha))/newd2);
end

% Calculate x1, x2, y1 and y2
x1 = newd1*cos(alpha);
x2 = newd2*cos(beta);
y1 = newd1*sin(alpha);
y2 = newd2*sin(beta);
x1 = real(x1) - d/2;
x2 = d/2 - real(x2);

% Calculate x and y
x = (x2+x1)/2;
y = real((y1+y2)/2 + 5);
end
### Appendix J – Calibration Data

<table>
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<tr>
<th>Distance between magnet and sensor (mm)</th>
<th>Hall Effect Sensor 1 Voltage Output (Volt)</th>
<th>Hall Effect Sensor 2 Voltage Output (Volt)</th>
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<tr>
<td>Distance between magnet and sensor (mm)</td>
<td>Hall Effect Sensor 1 Voltage Output (Volt)</td>
<td>Hall Effect Sensor 2 Voltage Output (Volt)</td>
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# Appendix K – Data Collected and Calculated

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<th>Calculated X (mm)</th>
<th>Calculated Y (mm)</th>
<th>Fitted X (mm)</th>
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