The Development of a Novel Sleep Position Monitoring Sensor

By

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Abstract

Obstructive Sleep Apnoea (OSA) is a prevalent public health issue, with 60% of cases due to sleeping supine predominant, a condition termed positional OSA (Heinzer et al., 2018). To correctly diagnose this condition, it is essential that body position during sleep is accurately monitored, as well as non-invasively. This is a broad and growing area of research with multiple technologies posing solutions. However, there are still several challenges and shortcomings in current technologies. These include, privacy, usability, the need for personalised training of classification models, high-cost and complex signal processing. Consequently, current methods for monitoring body position are deficient.

This thesis describes the evolution of a novel sleep position monitoring system over three iterations. The research commences with a systematic literature review to identify and evaluate the current technologies in this field. The review is followed by a needs analysis. The major project stakeholders of end-users and sleep health experts completed questionnaires to aid in understanding project requirements. From these findings the sensor was designed to be a wearable that mounts directly to the skin over the sternum.

An important body of the thesis is the iterative design process to produce a novel first prototype of a sensor that meets the requirements identified from the review and customer analysis. The developed sensor has gone through extensive evaluation over multiple iterations to ensure the shortcomings of existing methods are met. To test the reliability and repeatability of the developed prototype a custom 3D printed testing mount was designed and developed. Resolution tests conducted at 15º and 30 º show that the sensor is able to repeatably and accurately realise position. Calibration tests conducted show that the sensor is successfully able to apply offsets to all positions to make data straightforward to interpret. A low standard deviation of measurements shows good agreement between the expected and measured position. Ultimately, the efficacy of the developed technology needs to be validated. Future work identified involves a miniaturised and precision manufactured iteration to be developed and tested on human subjects in overnight studies.

It is believed that this initial design is a step towards the realisation of a body position sensor that is simple, unobtrusive and enables easy calibration. There is the potential for the sensor to be used in other applications including positional OSA treatment and sudden infant death syndrome (SIDS) prevention.

Declaration

I certify that this thesis:

1. does not incorporate without acknowledgment any material previously submitted for a degree or diploma in any university
2. and the research within will not be submitted for any other future degree or diploma without the permission of Flinders University; and
3. to the best of my knowledge and belief, does not contain any material previously published or written by another person except where due reference is made in the text.

Signature of student.. ....
Print name of student...Amelia Carter
Date: 6th June 2022

I certify that I have read this thesis. In my opinion it is/is not (please circle) fully adequate, in scope and in quality, as a thesis for the degree of Bachelor Engineering (Biomedical) (Honours)/ Master of Engineering (Biomedical). Furthermore, I confirm that I have provided feedback on this thesis and the student has implemented it minimally/partially/fully (please circle).

Signature of Principal Supervisor: Karen has confirmed her support of submission via email. Kristy is also aware of this confirmation (Cc'd in email).
Print name of Principal Supervisor...Karen Reynolds
Date: 6th June 2022

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Chapter 1: Introduction

Obstructive sleep apnoea (OSA) is a common sleep disorder affecting up to 49% and 23% of middle-aged men and women respectively (Heinzer et al., 2018). OSA is characterised by the partial (hypoponea) or complete (apnoea) pharyngeal collapse during sleep (Figure 1) (Heinzer et al., 2018). This loss of airflow can result in sleep fragmentation or fall in blood-oxygen saturation, leading to both physiological and neurocognitive effects including daytime sleepiness and depression and, consequently, reduced quality of life (Joosten et al., 2014).

Figure removed due to copyright restriction

Figure 1: Normal breathing during sleep (left) – Complete pharyngeal collapse, OSA (right) (Sibelmed)

Body posture has a major effect on sleep related breathing disorders (Oksenberg et al., 2010). The beneficial effects of sleeping in the lateral position and the harmful effects of the supine posture on breathing abnormalities have been consistently reported (Figure 2) (Oksenberg et al., 2010).

It is estimated approximately **60%** of OSA cases are due to sleeping in the supine position

(Heinzer et al., 2018)

This condition is termed 'supine predominant' or 'positional obstructive sleep apnoea' (POSA) (Heinzer et al., 2018).

Figure removed due to copyright restriction

Figure 2: The four main sleeping postures (a) supine, (b) left lateral, (c) right lateral and (d) prone (Jeng and Wang, 2017)

With a high prevalence of adults suffering from POSA, the monitoring of body position has become of high importance. It is essential that the body position of an individual under sleep assessment is accurately monitored to ensure any relationships with other physiological measurements are identified. Sleep assessments undertaken in sleep laboratories traditionally involve a sleep health expert observing and recording the participant's body posture throughout the night with a video camera for reference (Joosten et al., 2014). Sleep monitoring at-home is a growing area and therefore alternate methods have been adopted (Catcheside, 2021).

Polysomnography (PSG) is currently the ‘gold standard’ for sleep monitoring which assesses multiple sleep characteristics including position with a positional sensor attached to the chest (Jordan et al., 2014). These systems are used in both sleep clinics and in the home. The complicated set up for PSG can interfere with sleep due to the invasive nature of chest straps and wires, thereby restricting movement. This can result in increased time spent in the supine position (Jordan et al., 2014). Commercial products available to monitor position predominantly consist of an accelerometer embodied into a wearable. The sensors most frequently researched are also wearable accelerometers (Fallmann et al., 2017), with attachment sites including wrists, ankles or the chest.

Some studies have attached a mobile phone to the body, using the inbuilt accelerometers to monitor position (Ferrer-Lluis et al., 2020). Non-contact methods of smart mat systems embedded with pressure sensors, vibrational sensors, respiration-derived posture and Doppler radar have also been explored as methods of monitoring body position during sleep (Diao et al., 2021a, Li et al., 2021b, Liu et al., 2019, Liu et al., 2017). The high-cost and trade-off between size and accuracy of smart mat systems is consistently reported (Alinia et al., 2020). Cameras and Kinect sensor technologies have also enabled the continuous monitoring of body position overnight. These systems pose challenges of privacy and reduced accuracy from blankets obstructing the patient (Lee et al., 2015). The above methods commonly require calibration and personalised training of classification models to improve accuracy (Alinia et al., 2020, Jeng and Wang, 2017). Wearables, such as accelerometers, however, do outperform the other methods explored due to their portability, low cost and ease of use.

Standard body position sensors, those explored above, usually categorise position in to the four main positions seen in Figure 2 (Joosten et al., 2014). Such a broad classification ignores the graded effect of upper airway collapsibility and the rotation from supine to lateral trunk position (Joosten et al., 2014). Recent research has highlighted that this categorisation of sleep position may limit the identification of subtle relationships between posture and OSA severity (Tate et al., 2020). Therefore, exploring methods that accurately achieve higher resolution are of interest.

In this thesis, a novel sleep position monitoring wearable sensor is developed and presented. A comprehensive systematic literature review has been conducted on the use, accuracy, and limitations of existing methods for monitoring body posture during sleep. A needs analysis was conducted such that in conjunction with the review findings, a sensor could be developed that fulfills all the requirements. The design innovation ensures that shortcomings of existing methods are accounted for. The evaluations of customer needs ensured the sensor focused on three fundamental contributions of the design: (1) The sensor is unobtrusive, permitting natural movements during sleep; (2) The sensor accurately identifies, as a minimum, the four main sleeping positions; and (3) The sensor is not subject to noise, enabling straightforward data interpretation. The sensor was validated using a custom 3D printed testing mount and the performance results were presented.

The remainder of the thesis is organised as follows: Chapter 1 provides context and motivation for the development of a novel sleep position monitoring sensor. The current technologies to monitor body position during sleep are evaluated in a systematic literature review in Chapter 2. Chapter 3 details the needs analysis of the sensor, including surveys with stakeholders and completing quality function deployment. Chapter 4 discusses the evolution of the sensor with detailed descriptions of each iteration. Materials and testing protocols are outlined in Chapter 5. The sensor results followed by a discussion of the results are presented in Chapter 6. The conclusion and recommended future work for the project are in Chapter 7.

1.1 Motivation and Scope of Research

The high prevalence of POSA and therefore usefulness of accurately monitoring body position during sleep is essential in correct diagnosis. This thesis encompasses the design, building and initial operational validation of a first functional prototype for a novel body position sensor. The sensor is designed to meet the shortcomings of existing methods, whilst fulfilling all user requirements to produce a successful solution. Preliminary validation of the sensor is undertaken on a custom 3D printed test rig.

Chapter 2: Systematic Literature Review

2.1 Methods

2.1.1 Objectives

This review aims to analyse published articles that focus on technologies for monitoring body position during sleep. The Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) model was followed to identify, screen, select and critically assess relevant research.

2.1.2 Study Selection Criteria

The literature search was conducted in September and October 2021 in the databases PubMed, Web of Science and IEEE. The keywords were selected and operators 'AND' and 'OR' were used to produce the search strategy of *(Posture OR Position) AND (sleep monitoring OR sleep monitor OR sleep monitoring system OR sleep monitoring sensor)*. Due to the large number of articles, only articles published between 2012 to 2022 were included.

Studies completed in a research laboratory and studies using commercial products were included. Studies were excluded if body posture during sleep was not specifically classified. Articles that did not conduct overnight or long duration recording (>4 hours) were excluded. Studies were excluded if the four main positions of supine, prone, left and right lateral were not reported, as these studies do not present a wholistic method. Finally, if the number of subjects tested on was <2 or the full text was unavailable the paper was excluded.

2.1.3 Data Extraction and Analysis

The PRISMA model includes two major stages to analyse the articles. After removing duplicates, the articles titles and abstracts were screened. Articles that met the inclusion criteria were identified. The full texts of the articles included in the previous step were checked for eligibility. The final papers included in this review were identified as meeting all the inclusion criteria.

2.2 Results

2.2.1 Study Selection

The PRISMA model was followed for the literature search, the steps are outlined in Figure 3. The initial search across the three databases yielded 709 results. After removal of duplicates, screening and exclusion, 34 articles remained. The included articles were analysed based on the technology used to measure body position during sleep. Of the 34 included in this review, 10 used accelerometers, 3 used in-built smart phone accelerometer and accompanying application, 7 smart mat, 6 depth sensor, 3 infrared camera and 5 used other non-contact methods. The study cohort sizes were heterogeneous ranging from 2 to 92. Therefore, a review of the full-text articles produced 6 categories, one for each of the sensing technologies.

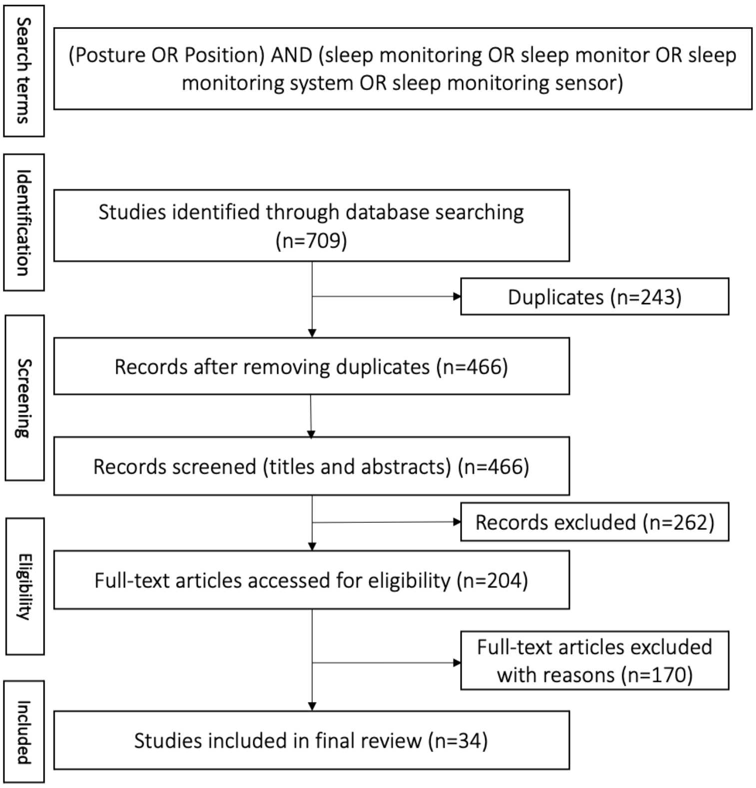


Figure 3: Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) flowchart

2.2.2 Categorised Results:

2.2.2.1 Wearable Accelerometer

The largest category of studies used a wearable 3-axis accelerometer. All 10 papers were able to monitor as a minimum the four main positions. Some of the papers explore the accuracy of trained classification algorithms in successfully identifying body position. Fallman et al (2017) conducted an overnight study with Shimmer3 accelerometers strapped to the chest and both ankles of two participants. The system achieved 98% classification accuracy when classifying eight positions. The authors address the challenge of wearables and their robustness and trade-off between tracking positions with finer granularity and energy efficiency. They also explored classifying only three positions; the accuracy of the generalised model was reduced however the efficiency of analysis improved. Other researchers have achieved similar accuracy with a posture monitoring system that involves training a personalised model (Jeng and Wang, 2017, Zhang et al., 2015). Fallmann et al (2017) did not include sensors on the wrists, stating that the arms remain in similar positions for all postures. Strapping accelerometers to only the ankles reduced the accuracy of the generalised model to 79.71% (Fallmann et al., 2017). Comparatively, Jeon et al conducted a larger overnight study with 11 participants, the classification performance was evaluated across seven different sensor placement combinations. Placing a single sensor on the chest obtained the same classification accuracy of 95% as placing a sensor on the chest and one on either one of the wrists simultaneously. Alinia et al also explored placing a single accelerometer on different body locations, finding the chest and thighs to be the most salient body sites (Alinia et al., 2020). Although accuracy was not specifically reported, Lokavee et al also used an accelerometer strapped to the chest, validated against PSG and successfully identified the four main postures (Lokavee et al., 2021). Researchers noted the prevalence of noise in the signal across all experiments due to body motion and loosening of the device (Jeon et al., 2019b). Mount position did change slightly due to roll over during sleep (Jeon et al., 2019b). The variability in sensing values between a loose and tight mounted device was also noted (Jeon et al., 2019b).

A high classification accuracy was obtained by Wrzus et al who strapped accelerometers to the sternum and right thigh of 92 patients spending the night in a home environment (Wrzus et al., 2012). Most felt undisturbed by the accelerometers, although 5.3% of participants reported that they felt restricted to move to prone position. Despite this, the results show that on average these participants spent 35.4% of the night in the prone position despite their concerns (Wrzus et al., 2012).

One study used a single patch-type accelerometer sensor attached to the left side of the chest (Yoon et al., 2015a). Like Jeon et al, the single sensor on the chest obtained high accuracy. The developed algorithm was tested on 13 subjects overnight finding only 0.12% of postures to be unclassified (Jeon et al., 2019b). Adhering an accelerometer to the suprasternal notch via a double sided patch, with a weight of 18g was also explored, obtaining a classification accuracy of > 97% on 30 participants (Mlynczak et al., 2020). The patch-type accelerometer research did not report any complications with sensor movement.

2.2.2.2 Smartphone Accelerometry

A series of recent studies by Ferrer-Lluis explored the use of a smartphone fastened to the sternum via an elastic strap. The authors analysed accelerometry signals recorded by a Samsung s5 and validated the data against PSG (Ferrer-Lluis et al., 2020). Detection in the prone position was not satisfactory, it was stated this could be due to artifacts. The same group of authors extended this research by developing an Android application called SleePos App, which is used for high resolution angle-based position monitoring (Ferrer-Lluis et al., 2021b). Their previous work suggested more precise sleep position technology is desirable as there is position variability between the four major postures (Ferrer-Lluis et al., 2021a). Following further development of the application the smartphone was fitted to 17 subjects overnight via an elastic strap (Ferrer-Lluis et al., 2021b). The attachment method proved to not interfere with sleeping in the prone position with three participants spending 37.9%, 48.8% and 29.6% in the prone position.

2.2.2.3 Smart Mat Systems

The use of smart mat systems for sleep posture recognition have recently been explored. Diao et al highlight how previous studies have proposed the use of larger mat systems. These have a high density of pressure sensors thereby increasing data processing complexity, costs and reducing portability (Diao et al., 2021b). The inefficiency and therefore redundancy of sensors located on the edge of these mat systems was also noted. The team trained a neural network and obtained an 86.35% accuracy for the four major positions by attaining pressure distribution of the chest, part of the shoulders and hips (Diao et al., 2021a, Diao et al., 2021b). To validate the feasibility of the miniature smart mat, both a subject-dependent and subject-independent model was tested (Diao et al., 2021a). The research group found the general model and the personalised model to achieve an accuracy of up to 79% and 95% respectively. The authors highlighted that the recall of the left and right posture is lower than others and that supine and side-lying posture are similar due to the size of the mat. Diao noted that classifying between supine and prone position is a challenge due to similar pressure distributions (Diao et al., 2021b). A recent study explored a pressure mat system for hospital beds, populated with 2048 1-inch^2 sensors (Doan et al., 2021). An extremely high accuracy of 99.9% in classifying the four main positions was achieved, however the system required training. Other research used both force sensitive resistive (FSR) sensors for the upper body and an infrared (IR) array sensor (Grid eye) for the lower body (Hsiao et al., 2018). This method obtained a comparatively lower accuracy compared to other studies of 88.05%. Ballistocardiogram (BCG) signals have been used in a novel posture recognition system. BCG signals were recorded from pressure sensors embedded in the mattress and position predicated from these signals (Zhang et al., 2019, Liu and Ye, 2018). These systems can be affected by clothing or blankets (Liu and Ye, 2018).

2.2.2.4 Depth Sensor

Sleep position classification using a camera is advantageous in that it has the ability to detect a wide range of information (Grimm et al., 2016). Cameras are also considered inexpensive compared to contact sensors (Akbarian et al., 2019, Grimm et al., 2016). Non-contact video-based approaches can detect sleep position however the data are more difficult to analyse then a wearable sensor (Lee et al., 2015). Lee et al experimented with mounting a Kinect v2, a sensor containing both time of flight (TOF) and infrared (IR) sensors, 2m above the bed on 20 subjects(Lee et al., 2015). The environment was arranged similar to a natural sleep environment with controlled temperature, lighting, humidity and noise level; however participants were not covered with blankets. Blankets pose challenges of differentiating between prone and supine position which is extremely important in POSA assessment. Other researchers have explored the use of Kinect sensors. They too did not use blankets in experiments (Liu and Payandeh, 2016). A more recent paper adopting a Microsoft Kinect sensor developed a software framework for both monitoring and analysis (Masek et al., 2018). This system was able to be used with a blanket covering, in complete darkness and for a 6-7 hour monitoring session. Analysis time for a single night session was under 5 minutes compared to the reported 30-60 minutes in other literature.

2.2.2.5 Infrared Camera

There are several reports on non-contact methodologies for estimating pose during sleep using IR cameras. Akbarian et al used a Point Gret Firefly MV IR camera to record 50 participants over a single night (Akbarian et al., 2019). Half of the data were used for training and validation and the remaining half were used as test sets. The authors found the best performing model to achieve 88% accuracy. In another approach, an IR-based sleep monitoring system required both pre-processing and data augmentation, achieving an accuracy of 76% and 91% with and without blankets respectively (Mohammadi et al., 2018). More recent research by the same group found the IR system to successfully detect four pre-defined poses and an empty bed at an accuracy of 95.1% using the pretrained network (Mohammadi et al., 2021).

2.2.2.6 Non-contact sensing

There is some research on the use of non-contact sensing methods, including vibrational sensing, millimetre wave signal, doppler radar, respiration signals and RFID tags. Millimetre wave signals have been used for vital sign monitoring by directing the waves to the body and the received signal strength (RSS) can be analysed to estimate breathing and heart rate (Yang et al., 2017). From these signals body posture identification can be inferred following data denoising and filtering. This system did require a personalised training for a high classification accuracy of 98%. Research using the doppler radar is yet to be tested overnight and the generalised model was not showing a competitive accuracy with other technologies (Higashi et al., 2019). An innovative respiration-derived posture (RDP) method based on the left and right lung respiration impedance signals has been explored (Liu et al., 2017). This method was unable to achieve a higher resolution than the four main positions (Liu et al., 2017). Using human body vibration to identify sleep postures has been introduced recently (Li et al., 2021b). The system involves a bed mounted vibration-based system that monitors vital parameters during sleep, features extracted from heart-beat motion cycles are used to classify position. Short-term experiments yielded an accuracy of 90.29% in identifying the four main postures. This method however relies on an accurately measured heart cycle to obtain body position. The use of passive RFID tags taped under the bed sheet creating a system called TagSheet has been developed. This system was able to achieve high accuracy posture identification and did not require any personalised training (Liu et al., 2019). However, the large size of the tags lowers the image resolution resulting in loss of posture details. Furthermore, the RF signal can be affected by surroundings.

2.3 Discussion

2.3.1 Main Findings

The review of the current literature shows there is an increasing interest in posture monitoring during sleep. The review identifies the variety of methods that are successful in recognising at least the four main postures with satisfactory accuracy. Authors highlight the benefits of contact-free sensing without using cameras thereby avoiding privacy violation issues (Li et al., 2021b). Technology that is minimally invasive is attractive for both clinicians and patients, it was found mounting a smart phone or accelerometer to the chest did not interfere with natural sleep position (Ferrer-Lluis et al., 2021b). The most commonly reported system identified in this review was positional sensing via accelerometry. The methods explored were conducted in laboratory research settings as well as in home settings and the recording limits are well established. The research showed that the major limitations include their high susceptibility to motion artefacts as well as consistency issues with firm and loose mounted accelerometers. Sensor movement did not occur in the patch-type accelerometers.

The use of IR cameras and depth cameras found considerably increased accuracy when the participant was not obstructed with blankets. In addition the weaknesses surrounding automated recording and analysis algorithms is that they need to be trained and tuned (Lee et al., 2015). Classification algorithms need to be re-trained when used in different lying positions, so they are therefore not versatile and are not ‘ready to use’ (Lee et al., 2015). Mat systems have relatively high accuracy however some do not distinguish between the two mandatory positions of supine and prone in POSA diagnosis (Diao et al., 2021b). Comparatively others have high accuracy when classifying the two positions however the mat is large covering the entire bed, posing problems of low portability and increased cost.

Both non-contact methods of using millimetre wave and doppler radar require personalised training to increase the accuracy, posing effectiveness limitations. The shortcoming of using vibration signals is they rely on an accurately measured heart rate to obtain position. Research using RDP methods rely on accurate acquisition of other physiological signals. The use of RFID tags proved to be the only ready-to-use system requiring no classification training however the signals are easily affected by surroundings. In addition, the systems did not have a high resolution.

One of the major issues around posture monitoring is user acceptance associated with the level of usability and comfort. Therefore, the position of the sensors, the number of sensors and the method of attachment to the body are important. The fewer attachment sites, whilst still obtaining accurate and complete information, the better the user’s perception. Jeon et al found that attaching a single accelerometer to the chest obtained the same accuracy as having sensors also attached distal limbs (Jeon et al., 2019b). The strapping of the phone to the chest in Wrzus et al gave users the perception they were unable to sleep in prone position (Wrzus et al., 2012). Although these participants spent a large portion of the night in the prone position this may reduce system acceptance due to their perception of the system. Also highlighted is the need for sensors that can be integrated into clothes or a method that enables wearing the sensor directly mounted to the skin such that wearable sensors can become more practical (Fallmann et al., 2017). User acceptance of a system is also linked to conducting the sleep study in a realistic environment. Therefore monitoring body position during sleep without a blanket is not an accurate sleep assessment (Lee et al., 2015).

Tate et al stated in their results that one week of monitoring may not always reflect sleeping behaviour of the participant in subsequent weeks (Smits et al., 2022). Therefore, multiple weeks of monitoring may be necessary. To improve effectiveness and improve user compliance, there is a need for a method that obtains long-term information accurately that does not require frequent re-calibration. The calibration frequency for the wearable accelerometers is not reported and may also influence the effectiveness of the system. All papers performed short-term testing however recording over multiple nights will confirm how effective methods are at obtaining accurate and non-interfering data. In addition, long term monitoring will determine how easy the methods are to interact with.

The effort, time and cost to install mats on top of the mattress as well as portability was highlighted in the literature (Fallmann et al., 2017, Yoon et al., 2015b). The installation concerns surrounding camera set ups was also addressed (Jeon et al., 2019b). Therefore, methods involving the wearable accelerometer or smart phone are potentially an effective choice for long-term monitoring. Battery life and frequency of charging is also a factor to consider in wearable devices and plays a role in user acceptance.

Efficiency of the positional data acquisition system involves both energy and temporal efficiency. Therefore, the software used must be able to process the data to obtain the relevant information. Lokavee et al were the only authors to present positional information in real time, with their smart mat system. Majority of the explored technologies require both pre-processing and postprocessing. Majority of the papers also required personalised classification models to be trained to increase accuracy. For every user to have their own model is costly as well as time inefficient. The ability to capture data, analyse the data and present information to patients, physicians or nurses is powerful. Thus, developing methods that track body position in real-time and are accessible to clinicians is required, as well as a system that does not require personalised training to yield accurate results.

2.3.2 Limitations of the Review Method

The studies retrieved for this review are recent however this is a current topic of interest and therefore there is rapid evolution of technologies in this field. Consequently, since commencing the review process additional relevant articles may have been published and new commercial products made available. The reliability of the systems is not conclusive due to the power of the trials. Of the studies reviewed, the largest reported population size was 92 people with the remaining studies averaging ~18 participants. The heterogeneity in study sample sizes as well as participants makes it challenging to give a conclusive assessment of which method is most reliable and suitable. Given the advancements in positional sensing technology it is expected that soon more complete and validated methods will be commercially available. The review reflects the broad research conducted on various sensing technologies with accelerometers being the most investigated for positional sensing. Although the only studies included had completed as a minimum extended testing, the studies were not explored over multiple sessions of extended testing.

2.3.3 Future Applications and Recommendations

This review shows that sleep position can be monitored using a variety of technologies. There is a need to explore these devices over longer periods and across multiple nights to determine important usability factors. It was also found that real time positional feedback is poorly reported. Research has focussed on the algorithms that classify position post monitoring. The research also focusses on the training of classifiers. As mentioned, the data sets were small, and the classifiers may not be easily adaptable to different settings and may require re-training. For the most accurate results a personalised model was required. Therefore, further studies could incorporate methods that do not require these complex algorithms and can be easily used across any environment without re-calibration or training. Future work may also incorporate methods that do not require complex signal processing to filter out noise and artefact in the case of accelerometers, smart mats, doppler radar, millimetre wave sensing and RDP signals. Additionally, minimising the steps involved in the system setup whilst being minimally invasive to the participant is preferable.

2.4 Conclusions

This review of the literature on technologies to monitor body posture during sleep shows the variability in research methods. It was found that wearable accelerometers are the most researched for overnight positional monitoring, however their recording limits are also established. Similarly, the non-contact methods of embedded pressure sensors, cameras and other non-contact methods were considered preferable as are non-invasive but do present their own limitations. All methods were successful in sufficiently identifying as a minimum the four main sleeping postures. Qualitatively the devices were able to preserve the natural sleep of the user. It was also highlighted the limitations that will aid in future developments of these technologies to achieve accurate posture monitoring during sleep that meets both user and sleep health requirements.

Chapter 3: Needs Analysis

The primary objective of the needs analysis was to understand the requirements of the major project stakeholders such that they were implemented into the developed solution. This follows the systematic literature review and is a phase in product development that must be completed to develop a successful and effective solution. In section 3.1 end-users and a sleep health expert completed questionaries, their responses aided in the development of the customer requirement list. In section 3.2 Quality Function Deployment (QFD), a tool for translating the customer requirements into appropriate technical design requirements, was completed to help develop a more customer-orientated product. Therefore, to identify the design requirements, the tools of competitive analysis, which are the findings of the systematic literature review, questionnaires with end-users and completing QFD enabled the important requirements of the future system to be identified. The final project aims are listed in section 3.3.

3.1 Customer Needs

3.1.1 Sleep Health Expert

The first task, to compile the design requirements, is to *hear* the voice of the customers – that is, gather data on the customer's needs. To do so a questionnaire was produced for an important project stakeholder, the sleep health expert. The sleep health experts interact with sleep assessment technology from setting up the sleep laboratory space, interacting with the user, calibrating the technology such that meaningful data is collected and finally interpreting the recorded data. The questionnaire was completed by Professor Peter Catcheside who is a sleep and respiratory physiologist at the Adelaide Institute for Sleep Health (See Appendix A). His knowledge in the area, especially of current procedures, limitations of procedures, issues related with user compliance, best practices, user feedback and interpretation of data was invaluable to understanding the project needs. Peter's complete responses can be found in Appendix A however a summary of his main thoughts on current technologies, their limitations and what is important is provided below:

- The current position monitoring device used in Peter's laboratory is accelerometer based and identifies the four main sleeping positions; however it is unreliable regularly losing calibration
- Issues with usability – device set up and download
- Problems and uncertainty if device is oriented incorrectly - data are challenging to interpret and accuracy can be reduced

- Most devices identify the four main positions and maybe the upright position; for some applications finer grained positional data may be useful
- There is an increase in the use of at home sleep monitoring technologies

3.1.2 End-user

Another major stakeholder in the project is the end-user, that is the people using the technology that monitors their body position during sleep. A survey was given to seven immediate family members, ages ranging from 25 to 94. The survey was to gauge insight into their thoughts on the current technologies for monitoring body position identified in the systematic literature review. Survey participants were asked what their most preferable technology was, secondly if the technology were to be a wearable where the most preferable location would be and thirdly what their most preferable technology would be if they were to use the technology at home without assistance. The questionnaire can be seen in Appendix B and the graphed results in Appendix C.

The results from Question 1 highlighted that the most preferable sensing method amongst the surveyed group was a smart mat. Non-contact sensing via a camera, and a sensor attached directly to the skin were second and evenly scored. Finally, a sensor strapped to the chest was the least preferable. Question 2 showed little variation in preference of sensor placement with the sternum ranking the most preferable. Question 3 showed that a smart mat and a stick-on sensor were the most preferable for at home use with no sleep health expert present.

3.1.3 Customer Needs

The responses of stakeholders were compiled, assessed and translated into a list of customer needs. The established customer requirements were tabulated and defined (See Appendix D). The requirements were ranked based on importance from the systematic literature review, sleep health expert and end-user findings and were used to build the House of Quality in section 3.2.1.

3.2 Quality Function Deployment (QFD) and House of Quality (HOQ)

QFD is a product development tool that assures the needs of the customers are met during the design, development, and production of the product (Verda O. Hinkle, 1995). QFD specifically identifies customer requirements and heeds those requirements throughout the whole design process.

The benefit of this tool is that customer requirements are directly translated to execution within the project. The central construct of QFD is the House of Quality (HOQ), which is used to identify and manage design trade-offs (Verda O. Hinkle, 1995). This works efficiently to ensure the customer voice is not misinterpreted at a subsequent project stage.

3.2.1. Building the HOQ

To build the HOQ first the customer requirements derived in section 3.1.3 were listed. These are qualitative wants and needs and are the voice of the customer. Included are what the customer would be delighted with even though it may not be a necessity. The customer's wants and needs (WHATs) were then prioritised reflecting their importance (See Appendix D). The importance was then given a percentage weighting, with the total equating 100%. For each of the customer requirements a quantifiable technical counterpart was established, the design requirement. Each of the design requirements produced were likely to affect, as a minimum, one of the customer requirements. Systematically all customer requirements were considered and their measurability. This translates the 'WHAT' to the 'HOW'. The produced engineering characteristics must be measurable such that target values can be established. Target values ensure that customer requirements are met in the finished product. For each of the design requirements a corresponding objective unit of measure was determined. The correlation matrix detected and balanced conflicts between engineering characteristics. This comprised the 'roof' of the house and relationships were indicated with symbols – blank = no relationship, '+' = slight positive relationship, '++' = strong positive relationship, '-' = slight negative relationship, '--' = strong negative relationship. The appropriate symbol was entered in the cell at the intersection of the matrix.

Next the relationship between the 'WHATs' and 'HOWs' was established and the relationship between each combination of the matrix. The purpose of this matrix was to determine how much each customer requirement is affected by each engineering requirement and helps ensure all 'WHATs' have been considered. Symbols corresponding to a value of 1, 3 or 9 represent the strength of relationship and are placed in the cell between the intersection of column and row between each of the requirements and specifications. A '1' is a weak relationship, '3' is a moderate relationship and '9' is a strong relationship, a blank cell indicates no relationship.

To establish the relative importance of the design requirements each relationship number rating of 1, 3 or 9 is multiplied by the prioritised percentage value of the customer requirement. The importance values can be seen at the bottom of the HOQ. Below the importance values are the target values for each of the HOWs. In setting the target values, consideration was given to values that would ‘delight’ the customers in the end-product. The developed product solution should aim to meet these targets.

To evaluate the competition the right-hand table is used to assess the current technologies that will compete with the thesis product. This determines to what degree each competing technology fulfills or addresses each of the customer requirements. How well each technology fulfills the customer requirement is ranked 1-5, 1 being least considered and 5 requirement is totally satisfied. The completed HOQ can be found in Appendix E.

3.2.2 Results of HOQ

The importance rating aids in prioritising the requirements of the project. From the HOQ the design requirements that ranked most highly were - *the level of potential harm, the number of identifiable body positions, number of steps to calibrate, user comfort and the number of natural body movements achievable.* The competitor evaluation of the five main technologies found all similar averages with the largest difference of 0.43 in fulfilling the requirement. This indicates that between the different technologies there is still a need for a higher achieving solution.

3.3 Final project statement

Upon the completion of the QFD analysis the project aims were refined. The project aims to develop and validate a first functional prototype of a body position sensor that is:

1. Unobtrusive and does not interfere with the user’s sleep.
    - This meets the important requirements of safety, user comfort and high number of natural body movements achievable
2. Accurately identifies, as a minimum, the four main positions of supine, prone, left and right lateral.
    - Fulfills the highly ranked requirement of the number of identifiable body positions.
3. Is not subject to noise and placement orientation has a level of flexibility to enable sleep health experts to easily interpret data
    - The requirement of device is easy to calibrate is considered in this aim such that there is flexibility in placement.
    - Data are easier to interpret with low noise and therefore the requirement of a high number of identifiable body positions is fulfilled

Chapter 4: Sensor Design and Experimental Protocol

To undertake the design and development of the sensor solution, an iterative double diamond design process methodology was adopted (Nessler, 2018). This chapter explores the second diamond of the double diamond design process (See Appendix F) which uses the project goals defined in section 3.3 to develop a solution. Ideation is a divergent process and involves the generation of many potential solutions. The solutions that were of interest for further exploration were evaluated. These main ideas followed a convergent path where they were prototyped, tested and analysed, until the best solution was realised. The output of the second diamond was the final solution to answer the original challenge.

Section 4.1 details the type of sensor to be developed based on the findings in Chapter 2 and 3. Section 4.2 explores the evolution of the sensor design over three iterations. Each of the iterations are evaluated with the third iteration being the final solution.

4.1 Evaluation of Sensor Type

The different sensing methods outlined in the literature review (Chapter 2) and the needs analysis findings (Chapter 3) were considered. The main technologies were tabulated and evaluated in Appendix G; from these findings it was decided that the developed sensor would be a wearable. The wearable would be designed such that in a future iteration it can be miniaturised and adhere directly to the skin. This eliminates the issue of sensor movement relative to the body, discomfort with strapping, and privacy concerns.

Prior to the sensor design the placement of the sensor was considered. It was decided to mount the sensor to the sternum, more specifically the manubrium, as this had been found to be most salient body site for monitoring lying posture (Alinia et al., 2020), and ranked highly in the end-user survey. The average adult sternal angle must therefore be considered in the sensor design. In a cadaveric study of preserved skeletal specimens the sternal angle ranged from 3° - 31° degrees relative to the facet (See Appendix H), averaging 16.6° and 15° in men and women respectively (Ball et al., 2021).

All previously reported studies were successful in identifying the four main sleeping postures and, in some research, the upright position too. It was decided that in this research, the developed sensor would aim to achieve 30° resolution due to the potential advantage of increasing resolution.

4.2 Sensor Design

4.2.1 Iteration One

All three iterations are based on identifying the movement of fluid within a sphere, using electrodes and a conductive fluid. A sphere was selected as this allowed the coronal and sagittal planes of motion to be monitored. For the application of measuring body position during sleep these planes give the necessary information, moving from upright to supine and from supine to prone around 360°.

In iteration one, a Ø30mm clear acrylic sphere was filled with 13.6ml ethylene glycol leaving a Ø10mm air bubble. Ethylene glycol was the internal liquid selected due its anti-corrosive and conductive properties, as well as being readily available. The surface of the sphere was populated with 54 equidistant Ø3mm brass rivets, each penetrating the sphere into the ethylene glycol by 2mm (Figure 4). There was an additional brass rivet penetrating the sphere 10mm such that it was always in contact with the internal fluid; this is the common rivet.

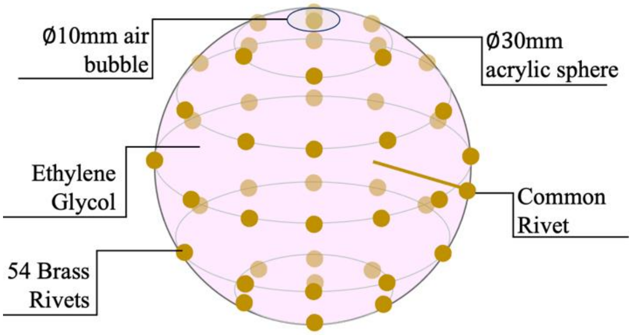


Figure 4: First prototype: Acrylic Ø30mm sphere filled with Ethylene Glycol and populated with 54 rivets

The common rivet was connected to a 5V output on the Mega2560, the selected microcontroller unit (MCU). The Mega2560 has 54 digital input/output (I/O) pins and therefore was the appropriate MCU for the number of rivets. Each of the rivets were connected to the digital I/O pins on the MCU.

The system worked such that the liquid in the sphere acted as a switch. If a pin was in the liquid the circuit is complete and the I/O pin would read ‘HIGH’. If the pin was in the air bubble, acting like an open switch, the I/O pin would read ‘LOW’. For the digital pins to read ‘HIGH’ they must receive a minimum input voltage of 3V and a ‘LOW’ reading must be less then 1.5V (See Appendix I). Therefore, each of the rivets were connected to a voltage divider circuit and connected to a digital I/O pin on the MCU, to ensure correct readings were made (See Appendix J). To determine body position each of the 54 pins were assigned a global coordinate, a longitude and a latitude (See Appendix K). To achieve a 30° resolution the pins were arranged in 7 latitudes, from 90° to - 90° in 30° increments.

The acrylic sphere was in two halves, facilitating drilling of holes for the PCB pins. The sphere was marked with the correct pin positions and 54 Ø1.3mm through-holes were hand drilled. The Ø1.6mm rivets were then press-fit in to the drilled holes such that they protruded 2mm within the sphere. Both the inside and outside of the sphere, where the pin inserted, was glued with gorilla glue. Sealing both sides ensured no moisture or humidity would remain within the rivets holes and therefore yield an incorrect reading. One of the pins was left unglued and was used to fill the sphere with ethylene glycol once the two halves of the sphere were press fit together and glued.

The air bubble size used was Ø10mm, as this only covered a single pin if centred around it. For the air bubble to cover two pins, 5° off centre of the pin was required. To determine position when the air bubble was covering two pins, their latitudes and longitudes were averaged. Increasing the air bubble diameter to Ø18mm was also explored. This allowed for a maximum of five pins to be in the air bubble at any one time. This did not increase the achievable resolution of the prototype, and the larger air bubble increased the settling time of the liquid due to greater momentum. A smaller air bubble of Ø5mm was explored such that only one pin at any one time could be in air; however this did not achieve a finer resolution. Therefore, the Ø10 mm air-bubble was selected for the iteration one prototype.

4.2.2 Evaluation of Iteration One

As this is the convergent stage of the double design process the built idea must be tested and iterated, prior to final design selection where more comprehensive testing is completed. To test the system design, each of the pins were exposed to the air bubble and then submerged in the ethylene glycol. This was repeated 10 times for each pin. If the pin was in the air the I/O pin was expected to output a 'LOW' and if in the liquid the pin should output 'HIGH'. It was noticed that the ethylene glycol left a film on the pins when the pin was moved into the air bubble. This produced a delayed response and, in some cases, an incorrect reading as the film would adhere to the pin, giving a reading indicating that the pin submerged. Another limitation of using ethylene glycol is the risk rating of the liquid. This chemical can be harmful if swallowed and can cause eye irritation (ChemWatch, 2022).

The method of detecting air bubble position by having a common pin constantly supply 5V to the fluid posed a potential issue of electrolysis. In the instance there was a variation in the pin's composition, the circuit would be between two different metals. Due to the constant exposure to direct current this metal variation may cause the possible chemical reaction of electrolysis. Another issue was the potential for the air bubble to split when it passes across the common pin. The bubble does not consistently recombine leaving two smaller air bubbles, and potential for inaccurate reading.
Another drawback of this method is that with miniaturisation of the protype, 54 individual electrodes may be hard to incorporate.

4.2.3 Iteration Two

The second iteration had three goals:

1. To determine a more suitable liquid contained within the sphere that is non-corrosive, safe and conductive
2. To use a different method of detecting the air bubble position that does not require a common pin to avoid the possibility of electrolysis and the bubble splitting
3. To produce a system that uses less pins

To achieve goal one, water was selected as being safe and conductive, and non-corrosive to certain materials including gold. The pins were therefore changed from brass rivets to gold printed circuit board (PCB) pins. Water also eliminates the problem of a film remaining on the pins when no longer submerged.

Goal two was achieved by eliminating the need for a common electrode. Each of the pins were moved to be connected to the analogue pins of the Mega2560. The microcontroller contains a multichannel, 10-bit analogue to digital converter. Therefore, the input voltages received between 0V and the operating voltage of 5V are mapped to integer values from 0 to 1023. This allows the state of the pin to be better understood.
The pin circuit also needed altering as there is no longer a common pin (Figure 5). The pull-down resistor of $10M\Omega$ ensures that when a pin is in air it is pulled down to a logical low value therefore gives an analogue reading ~0. The 10nF capacitor was used to smooth the direct current (DC) signal.

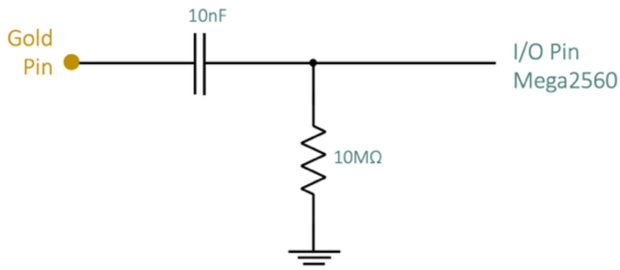


Figure 5: Pin circuitry, each PCB pin is connected to a capacitor and pull-down resistor and connected to an analogue I/O pin on the MCU

To determine if a pin was in air or water a different approach was followed. The logic of this is as follows and is completed on each pin:

- Step 1: Discharge the sensor pin – set the analogue pin to digital output and set LOW
- Step 2: Charge the sensor pin – set the analogue pin to digital output HIGH
- Step 3: Stop charging the sensor pin – set pin to analogue input
- Step 4: Read sensor pin voltage measurement – start analogue-to-digital conversion (ADC) – set pin to analogue input
- Step 5: Repeat for next pin

The proposed method utilised the capacitive properties of water. When the pin is charged in step 2 and stopped in step 3 the water acts like a capacitor storing this charge. Therefore, when the pin is read in step 4, the residual charge will be read when the pin is in water giving a logical high value. A high reading was considered anything greater then 700 on the analogue pin and the low readings never surpassed an analogue reading of 100.

Like iteration one, all pins were assigned a longitude and a latitude. The averages of the longitudes and latitudes for the pins in the air were determined to accurately locate the centre of the air bubble. This method of reading the pins eliminated the long common pin and the associated challenges of the air bubble separating and the potential for electrolysis.

To achieve goal three and reduce the number of pins a Ø30mm hemisphere prototype was explored, with 29 pins populating the hemisphere (See Appendix L). This also allowed for a more intuitive flat mounting surface to the user's sternum.

4.2.4 Evaluation of Iteration Two

Water was successful in meeting the desired properties of the internal liquid however, in the hemisphere the movement of the water was problematic. The air bubble deformed whilst moving. This was due to the constant change of water direction as result of the corner, where the flat bottom and curved surface meet. In addition, the surface tension of the water in the small volume was problematic. Therefore, the hemisphere form was not a viable option. The new method of reading the pins using the analogue I/O pins posed no problems.

4.2.5 Iteration Three

Based on the evaluation of iteration two, the goals of the third iteration were:

1. To revert the form of the sensor to a sphere
2. To reduce the surface tension of the water
3. To determine new pin positions such that higher and consistent resolution is achieved, whilst maintaining a reduced number of pins

The third iteration was built using a ∅20mm acrylic sphere. To reduce the surface tension of the water, isopropyl alcohol (IPA) was added. A 20% IPA solution reduced the surface tension of the water from $72 dyn/cm$ to $33 dyn/cm$ (Park et al., 2016). Within the spherical form and the reduced surface tension the ∅10mm air bubble moved smoothly tracing the curved edge with no distortion.

The pin placement remained in a single hemisphere, populated with 29 gold PCB pins. As with the previous two iterations, through-holes were hand drilled and pins were glued. The sphere was press-fit together, and one pin was left unglued such that the sphere could be filled. However, the mounting surface changed such that the latitude lines were parallel to the ground. This ensures the resolution, when moving from supine through right lateral, prone and left lateral, is consistent. The pins only populate the top hemisphere as the bottom indicates a user's bed is at a greater angle than 180° or someone bending further forward than 180° and for this application those angles are not relevant. The pin arrangement and assigned pin longitudes and latitudes can be seen in Figure 6 and Appendix M. To determine the air bubble position, the latitudes of the pins in air are averaged. The longitudes of the pins in air are also averaged. Flowcharts can be found in Appendix N, that outline the steps of the program. The method used in iteration two of detecting air bubble position by charging and discharging the pins was also used in this final iteration. Each of the pins were therefore connected to the same circuitry as seen in Figure 5 of iteration two.

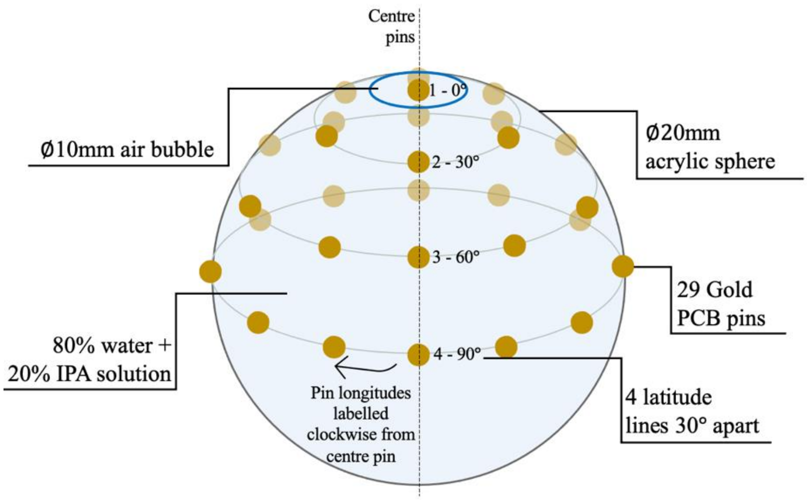


Figure 6: Front view of sensor, the backside is the mounting surface attached to the sternum. Latitude lines 1-4 and their corresponding latitudes are indicated. Longitudes are labelled clockwise starting from the centre line indicated

4.2.6 Evaluation of Iteration Three

Goal one of iteration three was achieved as the sensor form was reverted to a Ø20mm acrylic sphere. The surface tension of water was reduced by ~half by using a 20% IPA solution, therefore goal two was achieved. New pin positions were determined such that a consistent resolution was maintained through all planes of motion, and the design still only required 29 pins.

4.3 Integrated System Components

The sensor system consists of two separate parts. One part is the wearable, which is adhered to the user's sternum, whilst the other is an external control unit. The components of each of these parts are outlined in the sections below and illustrated in Figure 7.

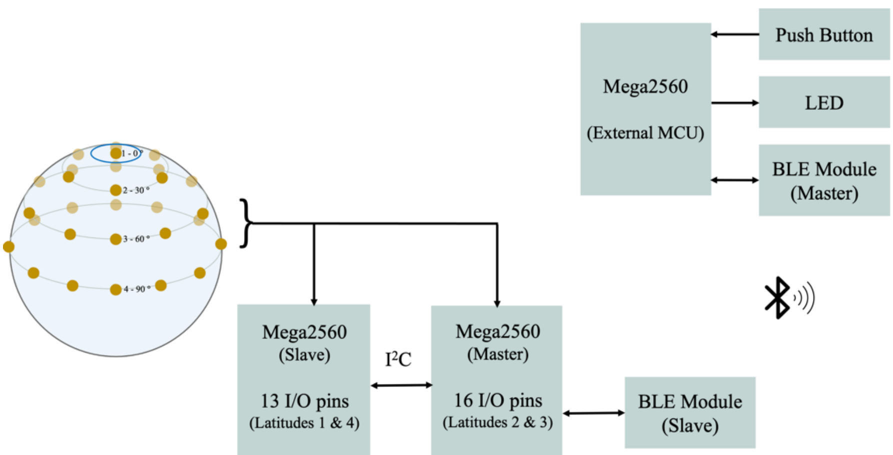


Figure 7: System component relationships

4.3.1 Components of the wearable part of the system

Microcontroller Units

The sensor designed in iteration three was connected to two Mega2560 microcontroller units (MCUs) each with 16 analogue inputs, since the sensor has 29 pins and therefore requires 29 analogue inputs. The two boards serially communicate via inter-integrated circuits (I^2C) communication. I^2C was selected as it maximises hardware efficiency and circuit simplicity, only requiring two bidirectional wires, a Serial Data Line (SDA) and Serial Clock Line (SCL) (Jacob et al., 2016).

Bluetooth Module (Slave)

An HC-10 Bluetooth Low Energy (BLE) V4.0 master/slave module for Arduino was required to send data to the external MCU. The BLE module has an ultra-low standby power consumption of 90uA-400uA and therefore is suitable for this application (Cirex, 2022). The module has an input voltage of 3.6V-6V, and was set to a baud rate of 9600, consistent with the MCU (Cirex, 2022). Using AT commands, the module was set as the slave unit and was paired to an external BLE module connected to the external MCU.

4.3.2 Components of the external portion of the system

Microcontroller Unit

An external MCU was also required as this receives and processes the data. In a future iteration a micro standard definition (SD) module may also be connected to store sensor data. A Mega2560 was also used here.

Bluetooth Module (Master)

Connected to the external Mega2560 is another BLE module, the same used on the wearable part of the sensor. This BLE was set to the Master and requests the air bubble position at 2Hz sampling rate. Previous research samples accelerometry data at 20-30Hz, however another research group found 1Hz sampling rate to be sufficient for posture recognition (Doan et al., 2021, Alinia et al., 2020, Manoni et al., 2020).

Pushbutton

Connected to a digital input pin of the external MCU is a pushbutton. The purpose of the pushbutton is to allow calibration of the initial position of the sensor relative to ground, allowing for flexibility in placement. This meets aim three of the thesis, which is - *there is flexibility in initial sensor placement such that the data is still easy to interpret.* Chapter 2 outlined the difficulty in interpreting accelerometer data when not orientated correctly on the chest. The sensor will be attached to a flat surface such that it can be easily mounted to the chest. An arrow will indicate the correct orientation for placement however, sternal angle differs between individuals and therefore this must be accounted for. The sensor will be orientated on its mounting surface at 20°. Therefore, for individuals with a sternal angle ranging between 15°- 25° the air bubble will be positioned over the pin with longitude and latitude 0, 0. However individuals with sternal angles outside this range, the air bubble will not be at position 0, 0. When the user adheres the sensor to their sternum the pushbutton will be pressed, and they must remain still for five seconds. The sensor takes five readings, and the final reading is stored as their initial longitude and latitude position. If the initial position is not 0, 0 an offset will be applied. When the master BLE requests the air bubble position from the Master MCU on the wearable part of the sensor, this position is also stored. The offset applied to the initial longitude and latitude to make them 0, 0 is then applied to all future readings. This allows all data to be easily interpreted.

Light-Emitting Diode (LED)

The LED is connected to a digital pin of the external MCU. When the calibration button is pressed, the LED flashes with each of the five readings taken. On the final reading the LED remains on for two seconds and when it turns off the user may move, and the senor commences recording.

4.3.3 Software

The open-source Arduino Software integrated development environment (IDE) was used, and all code was written in C.

Chapter 5: Experimental Methods for Validation

This section details the experimental methods to validate the effectiveness and ability of the third iteration sensor design in measuring body position. Section 5.1 and 5.2 present the experimental methods and testing procedure respectively.

5.1 Custom Testing Mount

To test the sensor in a controlled and practical environment, and to demonstrate its ability to measure position at the target resolution, a custom testing rig was designed and drawn on Autodesk Inventor. Typically, in the literature, technologies have been tested on subjects moving through controlled positions followed by an extended study allowing the participant to move naturally. The scope of this thesis is to produce a proof of concept and therefore does not include the miniaturisation of the sensor such that it can mount to a user's sternum. Therefore, the testing has been completed on a custom testing mount to ensure the sensor is able to achieve the target resolution of 30° in the coronal and sagittal planes.

The testing rig comprises two dodecagons orientated perpendicular to one another (Figure 8). Dodecagons were selected as each face has an external angle of 30° which was the target resolution of the sensor. In the centre of the rig is a pivoting beam, with a Ø15mm through hole in which the sensor is mounted. Engraved on the inner surface of the dodecagon is a semi-circle of 13 marks at 15° increments. The inner beam when parallel to the ground makes the bottom of the semicircle (Figure 8). The inner beam pivots and therefore can verify the sensor's ability to achieve 15° resolution in a controlled experimental set up.

The testing rig was 3D printed using Polylactic acid (PLA) filament. The inner beam was fastened between the dodecagons with two screws at either end allowing it to pivot. Experiments were performed at Flinders University in the Design Studio in March 2022. Detailed engineering drawings of the testing mount can be found in Appendix O.

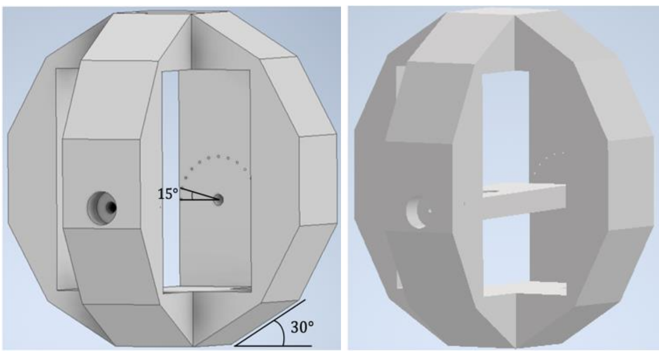


Figure 8: Custom testing rig – Two dodecagons orientated perpendicular (left). Assembly of testing rig with inner beam fastened and able to pivot to the marked 15° points on the inner dodecagon surface (right)

5.2 Testing Procedure

This section details the testing protocols for the sensor. Protocol one in section 5.2.1 ensures that the assigned longitude and latitude for each pin is correctly output when the pin is in air. Section 5.2.2 and 5.2.3 outline the protocols to test the sensor longitude and latitude resolution on an average sternal angle. The final protocol in section 5.3.4 places the sensor offset from 0, 0 and tests the calibration button.

5.2.1 Protocol One: Sensor Pins Response Readings

The calibration button was removed in this protocol, and the data transmitted to the external board were processed in Excel. The sensor was not mounted to the testing rig, instead held by the experimenter at the wires, such that there was no contact with the surface electrodes. The air bubble was reduced to a diameter of Ø5mm such that it covered a single pin at any one time. The external board was connected to the computer, powering the MCU board and the breadboard that the MCUs attached to the sensor were connected to. Each pin was exposed to air for ten seconds and the measured longitude and latitude were compared to the expected longitude and latitude. This was repeated ten times for each pin, to confirm repeatability. The difference in mean values between the expected and measured position was determined for each pin.

5.2.2 Protocol Two: Validation of Latitudes

The calibration button was re-connected. The sensor was taped in the hole of the centre beam of the testing rig, orientated as if it was attached to an average angled chest of 20°. In this position the air-bubble was centred around the pin with longitude and latitude 0, 0 (Figure 9). The centre beam was rotated from 0° latitude to 90° latitude in 15° increments, remaining for ten seconds in each position. This was repeated ten times and replicates a participant moving from upright to supine. The results were saved and exported to Microsoft Excel for processing. The average difference between the actual latitude determined by the testing mount and the latitude measured by the sensor was determined. If the difference is significantly different from zero there is systematic error present within the system.

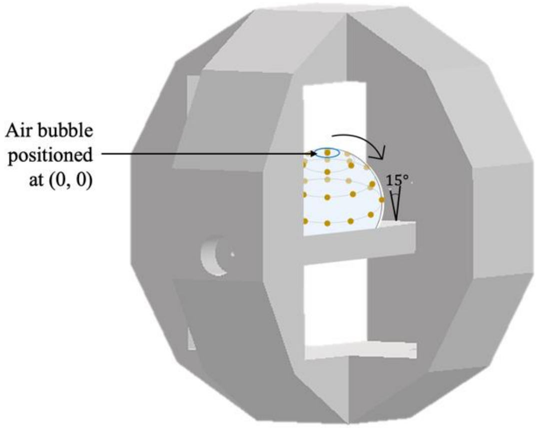


Figure 9: Experimental set up for validating latitudes. Sensor placed in hole of centre beam and taped. The centre beam pivots in 15° increments

5.2.3 Protocol Three: Validation of Longitudes Starting at 0,0

The sensor was mounted in the same starting position as section 4.3.3. The centre beam was rotated 60° from upright to position (60, 0) (Figure 11). The testing mount was rotated clockwise in 30° increments through 360° such that the sensor output was recorded on each of the dodecagon faces. This replicates a person sitting upright 30° and moving from supine through right lateral, prone and left lateral. The experiment was conducted ten times and all data were saved and processed in excel. The difference in means between the expected longitudes and measured longitudes was determined. The sensor-measured longitude positions were classified in to the four major positions as seen in Figure 10.

Figure removed due to copyright restrictions

Figure 10: Classification thresholds for the sensor measured positions (Smits et al., 2022)

A classification matrix was also used to describe the performance of the system to classify the four major positions.

The above protocol was repeated with the sensor positioned at latitude 90° instead of 60° to replicate someone lying flat on their back, supine (Figure 11).

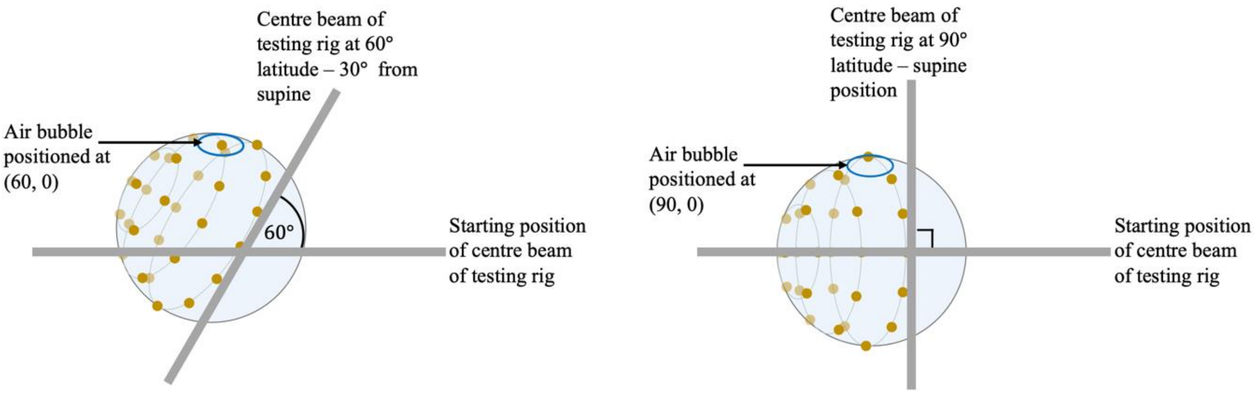


Figure 11: Experimental set ups to validate longitudes. **Left:** The sensor is placed in the centre beam hole and taped; the centre beam is rotated 60° such that the air bubble covers latitude line 3. The testing rig is then rotated to each face (30°). **Right:** The centre beam is moved to latitude line 4 (90°) replicating someone lying in supine and then the rig is rotated.

5.2.4 Protocol Four: Validation of Calibration Button

The following protocol was to test the functionality of the calibration button. The sensor was mounted to the testing rig at position 15, 120 to replicate someone with a sternal angle less than 15° and with the sensor tilted to the left.

The centre beam of the testing rig was then moved through 90° in 15° increments. The testing rig was then rotated through 360° in 30° increments. This replicates the user moving from upright to supine, then from supine, through right lateral, prone, left lateral and back to supine. This was repeated ten times. Data were exported to Excel and the average measured position before and after the offset calculation was determined.

Chapter 6: Results and Discussion

Section 6.1 presents the results from the protocols detailed in section 5.2.1 to 5.2.4, experimental challenges are also outlined in section 6.2. Section 6.3 contains the discussion, providing a critical interpretation of the data, limitations of the project are in section 6.4.

6.1 Results

6.1.1 Protocol One: Sensor Pins Response Readings

The sensor pins response readings, shown in Table 1, correctly respond when in air, with 100% accuracy. The sensor measured 0° error between the expected pin longitude and latitude for all ten repeats at each longitude and latitude of the pin when in air. This confirms the method of detecting air bubble position is repeatable and accurate. The 20% IPA solution provides highly responsive outputs with no noticeable lag in readings, confirming the solution to be a responsive medium.

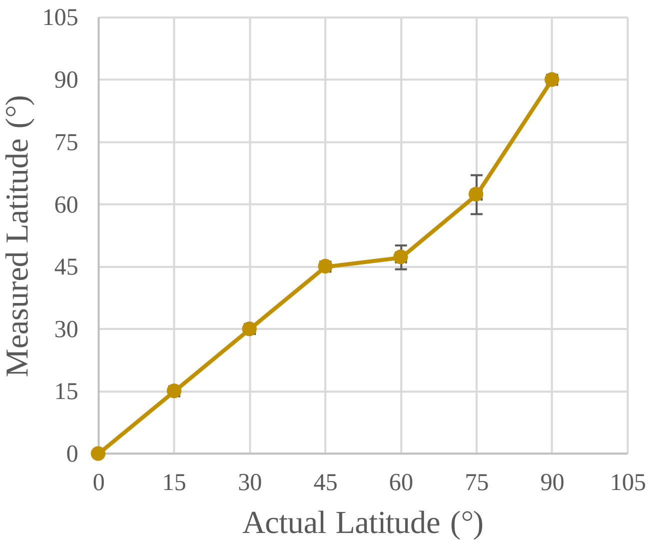
Table 1: Performance (difference of means) of the sensors pins' longitude and latitude when exposed to the air bubble

Latitude Expected (°)	Latitude Measured (°) – average (n=10)	Difference (°)	Longitude Expected (°)	Longitude Measured (°) – average (n=10)	Difference (°)
0	0	0	0	0	0
30	30	0	0	0	0
30	30	0	60	60	0
30	30	0	120	120	0
30	30	0	180	180	0
30	30	0	240	240	0
30	30	0	300	300	0
60	60	0	36	36	0
60	60	0	72	72	0
60	60	0	108	108	0
60	60	0	144	144	0
60	60	0	180	180	0
60	60	0	216	216	0
60	60	0	252	252	0
60	60	0	288	288	0
60	60	0	324	324	0
60	60	0	330	330	0
90	90	0	0	0	0
90	90	0	30	30	0
90	90	0	60	60	0
90	90	0	90	90	0
90	90	0	120	120	0
90	90	0	150	150	0
90	90	0	180	180	0
90	90	0	210	210	0
90	90	0	240	240	0
90	90	0	270	270	0
90	90	0	300	300	0
90	90	0	330	330	0

6.1.2 Protocol Two: Validating Latitude

Latitude accuracy and repeatability was tested by moving the sensor from upright, position (0,0), to supine, position (90, 0), in 15° increments. The device measured latitude error was found to be an average of 3.6° across the 7 latitudes (Figure 12). There was no discrepancy between actual and measured readings at latitudes 0°, 15°, 30°, 45° or 90°. The sensor measured latitude error was found to be an average of -12.7° over the 10 readings at each of the two latitudes of 60° and 75°. This suggests the sensor is under-reading and there is systematic error present within the system at these latitudes. The error associated with identifying latitudes 60° and 75° indicates that when the air bubble should only be covering the 60° latitude line it is covering both the 60° and 90° latitudes. This therefore obtained an average of 75°. When the sensor is rotated another 15° the latitude is expected to be 75°, the average of the 60° and 90° latitude lines. The sensor, however, is measuring 90° indicating the air bubble is only covering the 90° latitude line instead of the 60° as well. The substantial variation highlights that the 60° and 90° latitude lines are too close to one another indicating incorrect placement of the pins.

In this prototype, the pin locations were all hand-drilled resulting in alignment discrepancies from their assigned longitude and latitude locations. This can be rectified in future device construction.



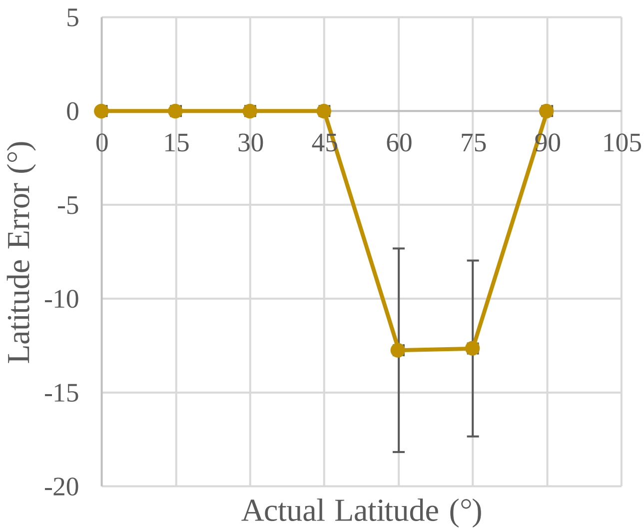


Figure 12: **Left:** Measured latitude closely replicates the actual latitude. The actual latitude corresponds to the pivot mark the centre beam of the testing rig is rotated to. Error bars show the standard deviation of ten repeats. **Right:** Error of latitude angle. The error experienced at latitudes 60° and 90° is due to imperfect alignment of latitude lines on the hand-drilled prototype. Error bars show the standard deviation of the ten repeats.

6.1.3 Protocol Three: Validating Longitude

The following section presents the sensor's ability to measure longitude, moving through 360° in a 30° upright position. This is to determine the accuracy in achieving a 30° resolution as well as sensor repeatability.

The sensor measured longitudinal error in this position was found to be an average of 4.1° (Figure 13). The longitude with the highest deviation (16.5°) was 210°. The largest mean error was at 60°, which was systematic and repeatable across all ten readings, hence indicating systematic error at this longitude. In addition, the sensor consistently over-reads at longitudes 210° and 240°. At longitudes 90°, 120°, 150° and 270° the sensor consistently under-reads.

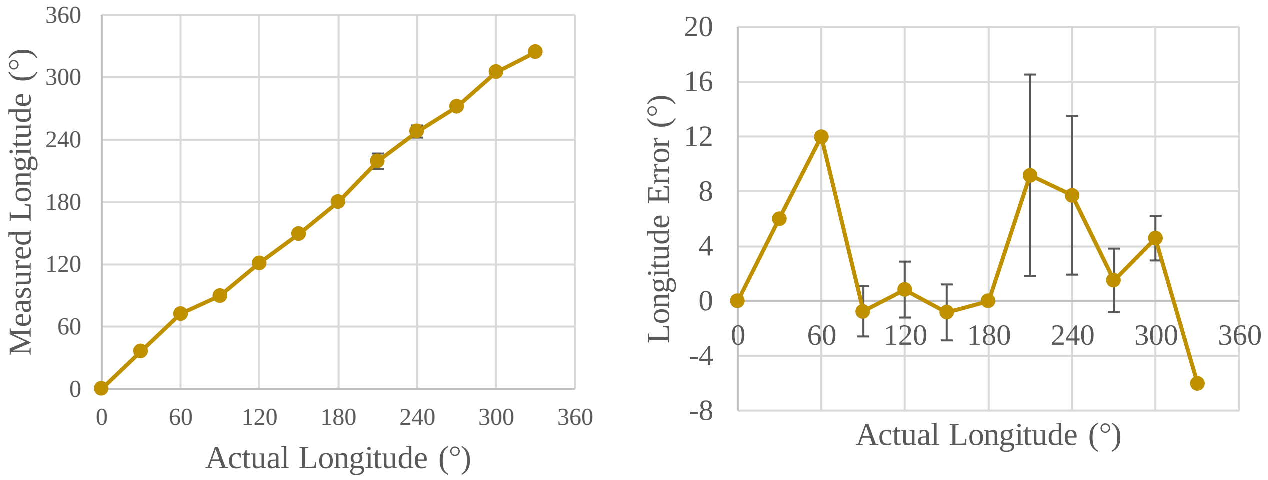


Figure 13: **Left:** Measured longitude at 60° latitude, closely replicates the actual longitude. The actual longitude corresponds to face the dodecagon is on. Error bars show the standard deviation of ten repeats. **Right:** Error of longitude angle. The error experienced is due to imperfect alignment of latitude lines and between pins in longitudinal positions on the hand-drilled prototype. Error bars show the standard deviation of the ten repeats.

The average error of 4.1° indicates the system is reliable with little error however the few outliers confirm systematic error due to the pin placement inconsistencies. Additionally, at 60° latitude the sensor measured 75°, as outlined in Section 5.2, therefore the longitudes measured are the average between the pins on both the 60° and 90° latitudes. The sensor measured 72° at 60° longitude, this is due to the density of pins. At this latitude the pins are 36° apart to maintain equidistance and therefore at this density there is some resolution loss.

The longitudes, emulating the user lying in the supine position (90° latitude), were then tested (Figure 14). The sensor measured longitudinal error in this position was an average of 1.3°. The longitude with the highest deviation (12.7°) and largest mean error was at longitude 210°, which was systematic and repeatable across all ten readings. Longitude 240° also consistently over read by an insignificant mean error of 3.5°. The results at 90° latitude (supine) are more accurate in achieving the 30° resolution compared to testing the longitudes at 60° latitude (30° upright), due to pin density. The minor discrepancies between measured and actual latitudes highlight inconsistencies in pin placement due to hand drilling.

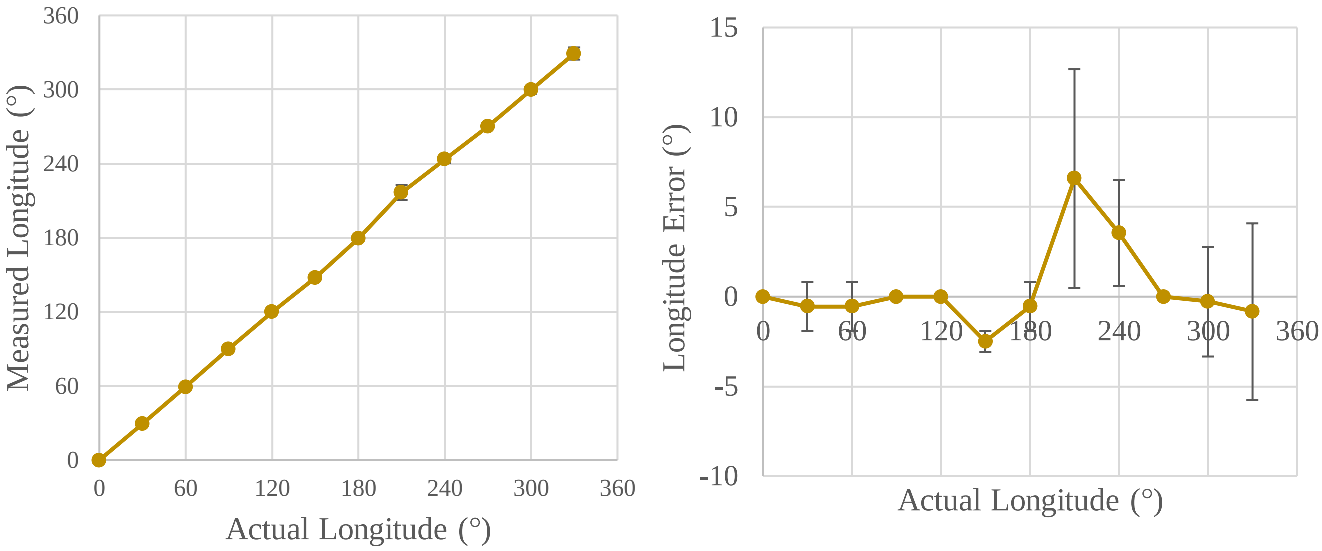


Figure 14: **Left:** Measured longitude at 90° latitude (supine), closely replicates the actual longitude. The actual longitude corresponds to face the dodecagon is on. Error bars show the standard deviation of ten repeats. **Right:** Error of longitude angle. The error experienced is due to imperfect alignment of latitude lines and between pins in longitudinal positions on the hand-drilled prototype. Error bars show the standard deviation of the ten repeats.

The results of this protocol highlight the importance of future iterations to be precision manufactured, ensuring all pins are positioned accurately. The tests should then be repeated on this future prototype to determine if the systematic error is eliminated.

A confusion matrix was used to determine the system's ability to classify the lying postures of supine, prone, right and left lateral with these systematic errors present. The averaged longitudes were taken at the longitudes 0°- 360° in 30° increments and the performance of the sensor to classify these into positions was compared to the known position. The system achieved an accuracy of 100% when in the supine position and 90% in 30° upright from supine (Figure 15). There is a discrepancy when 30° from supine, the system misclassified prone for left lateral at angle 210°, a false positive. This was most likely due to the pin placement error. However, this was the only misclassified position with the systematic error present, indicating the current prototype is a viable proof of concept.

n=12 (Actual \ Predicted)	Supine	Prone	Right Lateral	Left Lateral
Supine	3	0	0	0
Prone	0	2	0	1
Right Lateral	0	0	3	0
Left Lateral	0	0	0	3

n=12 (Actual \ Predicted)	Supine	Prone	Right Lateral	Left Lateral
Supine	3	0	0	0
Prone	0	3	0	0
Right Lateral	0	0	3	0
Left Lateral	0	0	0	3

Figure 15: **Left:** Confusion matrix in classifying lying posture into supine, prone, right and left lateral when at 60° latitude from the 12 averaged longitude sensor measurements. **Right:** Confusion matrix in classifying lying posture into supine, prone, right and left lateral when at 90° latitude from the 12 averaged longitude sensor measurements.

6.1.4 Protocol Four: Validating Calibration Button

The sensor was positioned such that the air bubble was offset from 0, 0 to position 15, 120. The calibration button was pushed such that for all future measured positions 15° would be subtracted from the latitude and 120° from the longitude. The measured latitudes (before and after the offset was applied) were plot at positions, 0° to 90° in 15° increments (Figure 16). The standard deviation across the ten repeats was 0, indicating the repeatability of the sensor.

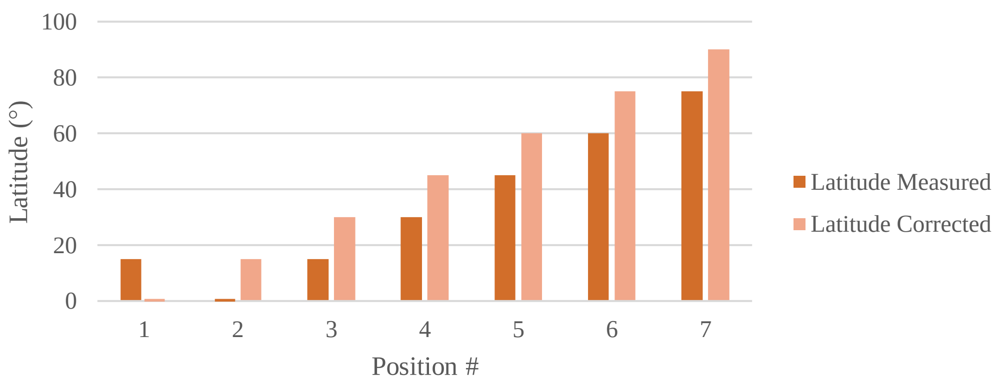


Figure 16: Measured latitude is indicated by the dark orange columns. The corrected latitude has an applied offset of 15° indicated by the light orange columns. The offset it correctly applied at all 7 latitudes. The standard deviation of the ten repeats is 0.

Figure 17 plots the measured and corrected longitudes at 12 positions, 0° to 360° in 30° increments. The average absolute error of the longitude reading was 2.72° at this offset position. The 120° offset was successfully applied to all calculations.

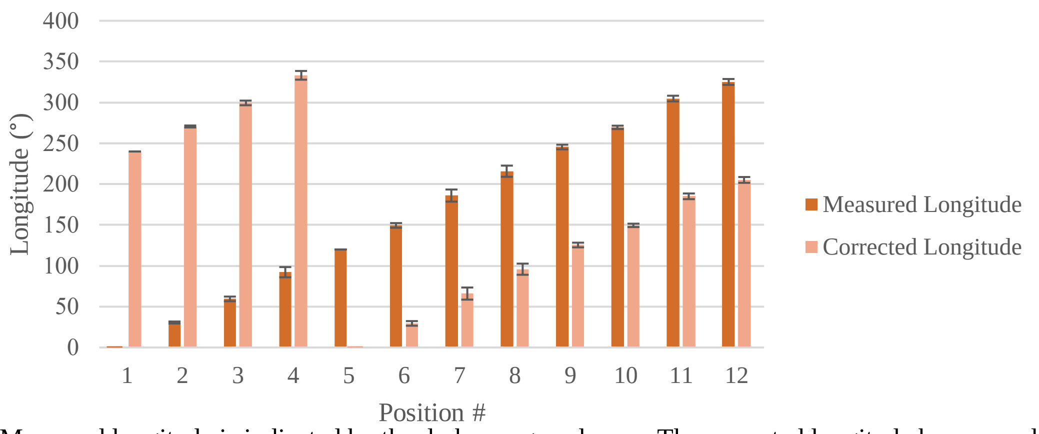


Figure 17: Measured longitude is indicated by the dark orange columns. The corrected longitude has an applied offset of 120° and is indicated by the light orange columns. The offset it correctly applied at all 12 longitudes. The error bars show the standard deviation of the ten repeats.

6.2 Experimental Challenges

The experimental setup using the 3D printed testing rig posed problems for mounting the sensor accurately and consistently across all tests. When setting up the experiments the sensor was placed in the circular hole in the centre beam and taped down. This was a potential source of error as the correct position was determined by sight, prior to reading the pins. To minimise this the sensor was marked with a Ø15mm circle, on the bottom hemisphere, parallel to the pins for protocol two. The sensor was placed in the hole in the centre beam such that the marked circle was not visible, this ensured that the air bubble would start over pin 0,0. For protocol three the first circle was wiped from the sensor and the circle was re-drawn at an angle such that the air bubble covered the pin with latitude 15° and longitude 120°. The lengthy wires (20cm) between the sensor and the microcontrollers added additional unbalanced weight to the sensor. To control this the wires were supported by taping the testing rig centre beam.

6.3 Discussion

The objective of this research was to present and demonstrate a first functional prototype of novel technology to determine body position whilst sleeping. This technology is composed of a sensor capable of identifying as a minimum the four major sleep postures, with a target resolution of 30°. The second aim was to develop a technology with flexibility in placement such that data are still easy to interpret. The final project aim was that the sensor would be unobtrusive to allow unimpeded sleep. This chapter summarises the results in Chapter 5 in sections that answer the research questions: Does the sensor accurately identify as a minimum the four main sleeping postures (Section 6.1)?; Does the sensor have low noise and flexibility in initial orientation such that data is still easy to interpret (Section 6.2)?; Does the sensor have the possibility to be unobtrusive (Section 6.3)?

6.3.1 Achieving Target Resolution

The results demonstrate: (1) The sensor was effective in classifying as a minimum the four main sleeping positions; (2) the sensor is successful in achieving the target 30° resolution. According to Figure 16 the sensor was 100% accurate in classifying position when in the supine position and 90% accurate when in 30° upright from supine. The sensor was able to achieve 30° and 15° resolution in the longitude and latitude position with low average error, thereby meeting the project aim of achieving a minimum of 30° resolution. There were discrepancies in some of the measurements due to the systematic error of pin placement. Measuring sleeping posture has been a growing area of interest. Traditional methods utilised smart mat systems, accelerometers and non-contact methods which have been classified to identify the four main discrete postures (Tate et al., 2020, Li et al., 2021a, Lee et al., 2019) . Other research has used video analysis and in clinic observations to also perform discrete position classification (Grimm et al., 2016, Mohammadi et al., 2021). However, the capability of accelerometers to resolve position to a finer resolution involves advanced signal processing due to the noise in the signal (Jeon et al., 2019a). Smartphone accelerometry is an alternative method available (Ferrer-Lluis et al., 2021c). There is recent research into the ability of identifying relationship between position and POSA severity with finer granularity (Tate et al., 2020). The technology presented in this thesis has the ability to resolve finer resolution positions discretely, avoiding the complications of noise and signal processing. The sensor has the capacity to achieve even finer granularity in future work with the addition of more pins. More specifically, comparing the results to a paper attaching an accelerometer to the chest and wrist, their trained model found over 90% accuracy for four main positions as well as upright except for prone which only achieved 79% accuracy (Jeng and Wang, 2017). The produced prototype has demonstrated the capability of measuring both useful and accurate data to classify the major sleeping positions. The small standard deviation and in some cases zero standard deviation in the results indicate a low noise system. The results suggest that this technology can provide sleep health experts with increased resolution and accuracy of sleeping position, therefore achieving research aim one.

6.3.2 Calibration Button

The sensor was designed to minimise incorrect initial placement orientation however there are instances this may occur. The calibrate button was designed to counteract these occurrences. To the author’s knowledge there are no existing wearable position sensing technologies that allow the user to place the device on and calibrate it to that initial position. The results demonstrate how the offset is applied to each longitude and latitude measurement such that the body position can be easily classified. Goal two of straightforward data interpretation if the sensor is not positioned at 0, 0 is therefore met.

6.3.3 Potential Unobtrusiveness

This study uses a single sensor to determine body position which in a future iteration will be adhered to the user's sternum. The produced proof-of-concept underwent an iterative design process such that the final concept could be scalable. A feasibility study by Mlynczak assessed the ability of a wireless wearable sensor, adhered directly to the suprasternal notch, to detect body position (Mlynczak et al., 2020). The sensor in the study had dimensions 33 x 39 x13 mm and a weight of 18g (Mlynczak et al., 2020). The weight of the filled sphere and submerged pins in the prototype developed in this thesis is only 3g. It is predicted that in a future iteration the sensor electronics will be miniaturised, and additional components incorporating a battery and custom PCB will be considered. Therefore, it is estimated the future sensor based on a smaller Ø10mm sphere with all components considered could have dimensions 12 x 30 x 20mm and a weight of 8g (Figure 18). This is smaller and lighter than Mlynczak's device, and as such, the proposed sensor has the potential to be considered unobtrusive and not affect the user's sleep, achieving goal one.

Figure removed due to copyright restriction

Figure 18: **Left:** Existing wearable accelerometer dimensions and weight (Mlynczak et al., 2020). **Right:** Proposed dimensions and weight of future iteration of sensor.

6.4 Limitations of research

There are a number of limitations to this research. Firstly, the hand-made prototype was tested on a custom 3D printed testing rig. This introduced manufacturing limitations which should be improved in future iterations. This will most likely increase accuracy and repeatability further. Therefore, there was no assessment of the efficacy of the system in the home uncontrolled environment. Secondly, each of the protocols involved only ten repeats and extended testing needs to be conducted on the sensor to determine the reliability as well as repeatability. Thirdly, there was no assessment of the efficacy of the system on a real person in the home uncontrolled environment. A thorough validation following iterative prototype development and miniaturisation, including wireless data transmission, should be tested extensively on human subjects in overnight studies.

Chapter 7: Conclusions and Future Work

7.1 Summary

This thesis presented a novel method for measuring body posture during sleep. The proposed sensor elucidates information, with increased resolution, that is not widely available in current methods. Additionally, the device enables more straightforward interpretation of data and therefore may assist in the more accurate identification of individuals with POSA. The main research tasks completed in the thesis are outlined as follows:

1. The completion of a systematic literature review evaluated the current technologies used for sleep position monitoring to aid in the diagnosis of POSA.
2. Undertaking a requirements analysis was essential to meet project aims and eliminate scope creep and therefore timeline blowouts. The analysis consisted of feedback from both end users and sleep health experts. The results were processed and tabulated to a list of customer requirement. The developed customer requirements were then prioritised and translated into a HOQ.
3. Three design iterations were completed. The final iteration was the solution developed and the integrated system was outlined.
4. A custom 3D printed testing mount was designed to test the prototype
5. Sensor accuracy at various angles of latitude and longitude was measured on a custom test rig. The results show that the developed sensor can realise the target 30° resolution with a maximum of 12.7° error, and achieve classification accuracy of the four main sleeping positions at 96%. The sensor can be calibrated such that data are easy to interpret if misaligned initially.
6. The accuracy of the developed sensor was consistent with competitive products (Jeng and Wang, 2017). There is a need for future work to be undertaken on the sensor such that it is ready for commercial use. The proposed future sensor has the potential to be smaller and lighter than existing wearables (Mlynczak et al., 2020).

7.2 Conclusions

According to the validation results of the developed proof of concept, conclusions are summarised as follows:

A. The developed sensor was able to *realise as a minimum the four main sleeping positions* with small error, thereby meeting project aim two. The capabilities of the designed sensor can be enhanced by re-producing a precision manufactured prototype eliminating systematic error.

B. The calibrate button was successful in accounting for a tilted initial placement and there was minimal standard deviation between samples, thereby meeting project aim three of *developing a system not subject to noise and ensuring data are interpretable if orientated offset from an initial position of 0, 0*.
C. There is a need for future work to be undertaken on the sensor such that a usability study can be conducted. This will determine if project aim one of *developing an unobtrusive sensor* is met.

7.3 Future Work

Based on the research achievement in this thesis, subsequent implementation and development work can be performed to further ready the sensor for commercial use. The future direction of research can be performed as follows:

Miniaturisation of Electronic Components: The miniaturisation of the sensor is an essential progression of the project. The electronics attached to the sensor will need to be miniaturised such that they will comfortably fit within a wearable, achieving the projected size seen in Figure 18. A custom PCB with the necessary 29 analogue pins and pins for BLE must be included. A battery, preferably rechargeable in the interest of design for longevity and being environmentally conscious, must be determined. The battery must be connected to the MCU to power the sensor in a compact and safe manner. The external control also does not require such a large MCU as only for pins for BLE, a digital pin for the LED and one for the pushbutton are required. Data storage must also be considered.

Development of the Sphere: The sphere in this research is Ø20mm in diameter with 29 pins, each connected to their own circuit. A smaller sphere, preferably Ø10mm should be precision manufactured. The possibility of populating the whole sphere with pins should also be explored. In the current design the pins are only placed in one hemisphere. Therefore, in the instance the sphere is tilted excessively, the air bubble will move beyond the bounds of the pins. Therefore, populating the entire sphere with pins would account for excessive misplacement of the sensor. There is also the possibility of reducing the number of wires by connecting each of the pins together with varying resistor values between. Having variable resistor values allows predicted analogue readings to be assigned to each pin position and their state can be understood.

Sensor Housing: The sensor and associated electronics will be housed such that it can adhere directly to the sternum. The housing must be comfortable for the user and permit easy and strong adhesion to the skin. It is expected a silicone housing would be used since this material features the properties of moisture resistance, flexibility and could have an opening on the outer surface for battery replacement or battery charging. The silicone mould would ideally be such that it is curved in shape therefore removing a pressure point of the spherical sensor. An adhesive that is hypoallergenic would be required. The external control would be housed in a small remote such that the user can easily place it on their side table. This will also be compact in the interest of portability. Universal design principles must be followed to ensure there is a focus on delivering a user-friendly and comfortable device. The housing decision must be based on extensive usability research and involve further surveying of end users and sleep health experts.

Extended Sensor Testing on a Subject: Further testing is required with the miniaturised prototype. A full usability study should be completed to receive feedback on the ease of use of the system, including use of the external remote for calibration, and the mounting of the sensor the sternum. The sensor accuracy and consistency will need to be validated on human subjects. The sensor should be tested in overnight studies on multiple participants, validating the sensor against a commercially available sensor or video analysis.

Other Applications: The current research focuses on the use of the sensor for POSA diagnosis. The sensor has the potential for use in other applications, including the treatment of POSA. The sensor can be paired with haptic feedback to notify the user to turn from the supine position to avoid an apnoea event. The sensor could also be used on infants, sleeping in the supine position is recommended to reduce the risk of sudden infant death syndrome (SIDS) (Sperhake et al., 2018). Pathophysiological mechanisms can be avoided when sleeping in the supine position. These mechanisms may lead to hypoxia or death in the prone position (Sperhake et al., 2018). Therefore, the sensor could monitor position and alarm parents or carers if the infant has moved to the prone position. Bed ridden patients who are unable to move independently may also benefit from this sensor. The sensor could notify carers or nurses when the patient has remained in a single position for an extended period. Frequent rotation avoids patient frustration and the development of pressure ulcers. It was found that three-hourly turning with a 30° lateral tilt was more effective at pressure ulcer prevention compared to six-hourly turning with a 90° lateral tilt (Jocelyn Chew et al., 2018). The proof-of-concept developed in this thesis was successful in achieving 30° resolution and therefore would be suitable for this application.

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Appendices

Appendix A: Sleep Health Expert Questionnaire

Return

Questionnaire completed by Professor Peter Catcheside on 23rd November 2021.

Existing methods:

1. What methods are currently being used in your laboratory for monitoring participant body position/ posture during sleep?
   - The default position sensor is a Compumedics sensor (https://au.neuromedicalsupplies.com/product/position-sensor/), which outputs step voltages according to 5 positions (left, right, back, prone, upright), but is not entirely reliable as the calibrations seem to go bad quite often. This also plugs into a single dedicated 3-pin connector port sometimes also needed for a Compumedics external sync cable, which then displaces the position sensor. Typically sampled at 1 to 20 Hz.
   - https://www.medys.be/dc-body-position-sensor-kit-compumedics-e-series-c.html to deal with the above issue we have used a battery powered 2 pin device which does the same job, but seems to be much more reliable.

2. What other methods for body position monitoring during sleep do you have experience with?
   - BuzzPOD http://www.buzzpod.com.au/
   - Video (manual confirmation of body position)
   - Trialed https://mmid-group.com/portfolio/sleep-positioning-trainer-nightbalance/, before that device as acquired by Philips.
   - Embletta polysomnography (PSG so multi-channel) acquisition device (has in-built position sensor)
   - Somte portable PSG acquisition device (in-built position sensor)

3. In your experience what are the major limitations of the current sleep posture monitoring methods?
   - Reliability – especially Compumedics sensors that seem to regularly loose calibration.
   - Useability (e.g. BuzzPOD) device setup and download

- Synchronisation with sleep signals when sleep vs posture signals are acquired with different systems.
- Software/analysis tools to analyse position shift data (I/we developed my own to support research needs).
- Problems/uncertainty with device positioning on the body. E.g. some people put them on upside down. When we have tried to acquire sleep and position data from multiple devices such as BuzzPOD and Embletta sleep acquisition device both vying for space on the chest one has to be rotationally displaced to make room for the other; making for uncertainty regarding accuracy of either device.
- Most devices reduce position into basic quadrants e.g. basic tilt switch outputs or via rotational cut-offs to classify body position into 4 rotational quadrants plus sometimes a 5th upright classification which is useful to know out of bed events. In some respects this is good/fine and simpler than dealing with finer grained rotational information which may or may not be useful. Ultimately supine vs non-supine is the primary focus, but for some applications it would likely be useful to retain finer grained positional data.

4. On average how long does it take to set up the PSG equipment on a patient?
    - A standard full PSG setup (EEG leads etc) takes around 30 minutes, but can take longer for research studies. Position sensor setup (e.g. BuzzPOD strap around the chest) is relatively simple/quick, although as soon as any form of measurement or treatment requires any form of participant co-operation the participation rate starts to decline.

5. What is some of the patient feedback surrounding the PSG setup you have received?
    - Most people find PSG leads etc a little annoying, uncomfortable and more difficult to sleep with (e.g turning/moving in bed is a bit more restricted - still possible, but leads can get tangled up), but for the most people mostly sleep OK.
6. How is body position information currently received or viewed?
   Ie. real-time feedback or logged and analysed later
    - In laboratory you can see posture changes real-time but most of the analysis is currently done off-line.

- See also response to 3. PSG systems typically rely on some form of a voltage change proportional to position and thus calibration file specific to the sensor. Some systems use accelerometers than can output a body rotational signal (but also including upright), which can be confusing to interpret when the relationship between output signal and body position is not necessarily clear or well documented (e.g. Embletta).
- BuzzPOD and most of the wearables require data download and analysis via software tools specific to the sensor/system or custom designed around the device output data. I wrote VBA analysis tools to time-sync BuzzPOD data and calculate more detailed nightly summary stats than otherwise possible.

7. How many nights of monitoring do you think gives an accurate representation of someone's sleep pattern?
    - That's pretty difficult to know/answer, but 1 night is clearly the minimum, 1 week more useful, but from other work we think that 2 weeks is perhaps around optimal to gauge usual sleep habits.

8. Is there an advantage to higher resolution position classification in all planes compared to just the four common postures of supine, prone, left and right lateral?
    - Possibly, but left, right, supine, prone (e.g. defined on the basis of 45° angle cut-offs – assuming the device is worn in the correct place/plane) plus upright are potentially the most useful. We've then typically collapsed those into supine vs non-supine or upright/out-of-bed, which may be the primary interest for defining supine-related sleep problems. Having said that, there could well be a different range of positions for which breathing is more problematic than others so finer-grained measurements could potentially be useful to test for and explore. I have seen Phil Terrill (UQ Brisbane) present radar plots with colour heat-maps to plot respiratory disturbance as a function of body position. That all gets more complicated to analyse and interpret, but could be a high value approach if/when combined with better measures of respiratory disturbance than currently used in mainstream practice.
    - Snoring, which is yet another measure not well defined in standard sleep measurement practice, if done better than usual (e.g. respiratory-gated acoustic

analysis including snoring frequencies plus sound pressure levels) could very usefully be combined with finer grained body position measurements I think.

At home-monitoring:

1. In your experience is sleep monitoring in the home a growing area?
   - Definitely. We know that sleep in a lab is not quite the same as sleep in the home, particularly when habits are involved. Covid has also increased the volume of home sleep studies being conducted I think.
   - PSG is also overly complicated and the traditional measurements we get from it are not very sensitive or specific to daytime complaints or potential health consequences so another good reason to measure sleep differently.
   - Motion based inferences about sleep (e.g. actigraphy) are very sensitive (sensitivity ~95%) but hopelessly non-specific (specificity ~30%) so will frequently classify wake without motion as sleep. So, at best, motion alone is only a guide around sleep habits and quality.
   - There are now several bed-sensor devices on the market that combine motion and ballistography plus a microphone (e.g. Withings sleep mat, we have more experience with but there are also others) to infer sleep from wake that do better than traditional actigraphy and seem to work pretty well. That also tries to estimate the apnoea hypopnea index (AHI) and is OK and quite useful, especially given multi-night recordings are then easily possible. However, my personal view is they/we could do better with more strategic measurements, including posture, which is difficult from an undermattress sensor… but perhaps not impossible.
   - There are also some sleep apnoea screening devices that can be pretty useful (e.g. ApneaLink, Resmed) for gauging respiratory disturbances. I'm not entirely sure if they have position sensors, but suspect they should/might.

2. To your knowledge what are the current at home body position monitoring devices?

Device	Device type
BuzzPOD	supine avoidance device
Nightshift	supine avoidance device
Nightbalance	supine avoidance device
Somte (Compumedics)	Home full PSG device

Embletta	Home full PSG device
Alice/Philips equivalent (sorry forgotten device name)	Home full PSG device
GreyFlash (UK company) and some others from same complany	Home screening device (no EEG)
ApneaLink (Compumedics)	Home screening device probably has posture
Probably others	

3. What are your thoughts on these take-home devices? What are the limitations?
   - Depends what the intended use is for, but they may be as/more useful than in-lab PSG.
   - The biggest limitation with sleep measurements in my mind is that most of the physiologically useful information content is largely ignored e.g.
     a. human scoring of the EEG in 30-sec epochs ignores signal features likely to be useful for understanding sleep quality.
     b. Manual scoring of respiratory events into apnoeas and hypopneas is very crude and throws away a lot of potentially informative info regarding respiratory disturbances and causal mechanisms
     c. Snoring is assessed particularly poorly and is largely ignored despite potentially being one of the most useful and technically feasible signals from which to infer breathing problems during sleep.
     d. Posture is a further key variable that is not really taken much notice of, but can have a profound effect on the upper airway and thus snoring and sleep quality.

Please number these monitoring and attachment methods from 1 being most preferable to 4 being least preferable

4. Wearable sensor – attached directly to the skin ie. via medical adhesive tape

3. Wearable sensor – attached via strap ie. velcro strap or buckle

2. Non-contact sensing – ie camera

1. Non-contact sensing – ie smart mattress / vibrational sensor

In the interest of time what is the most preferable method for set up – please rank the options

3. Set up camera – either a tripod or mount a camera to ceiling

- Note likely patient privacy issues/concerns regarding cameras in a bedroom

2. Strap a sensor to a part of the body

- Practical and potentially unavoidable with a feedback device.

4. Stick a sensor directly on the skin

- Could be fine/OK, but (presumably) requires daily setup so trades-off one time setup of mattress sensor or camera for daily application.

1. Place a smart mat on the mattress

- Perhaps the ideal assuming posture can be inferred – technically difficult but perhaps not impossible. In-pillow might be another target.

Return

Appendix B: End User Questionnaire

The following questionnaire was completed by 7 immediate family members.

Q1: Have you ever been a participant in a sleep study – either a take home monitoring kit or in a sleep laboratory? Please tick

- Yes – at home
- Yes – in sleep laboratory
- No

Q1a: If yes, what was your experience? Any thoughts on the setup of the monitoring equipment?

Q2: Have you ever been diagnosed with sleep apnoea?

- Yes
- No

Q3: Please number these monitoring and attachment methods from 1 being most preferable to 3 least being preferable

- Wearable sensor – attached directly to the skin ie. via adhesive medical tape
- Wearable sensor – attached via strap ie. Velcro strap or buckle
- Non-contact sensing via a camera
- Non-contact sensing via a smart mat on top of the mattress

Q4: Please number these attachment sites from 1 being most preferable to 3 least preferable

- Small of your back
- Sternum
- Suprasternal notch

- Side body – under pectoralis major

Q5: Please rank your preferences on the monitoring set up in the instance of take-home device

- Set up camera – either a tripod or mount a camera to ceiling
- Strap a sensor to a part of the body
- Stick a sensor to the skin
- Place a smart mat under the fitted sheet on the mattress
- Mount sensor to the side of the bed

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Appendix C: End-User Questionnaire Results

The responses of questions 3-5 of the completed end-user survey were averaged. The results can be seen in the Figures 19 to 21 below. The lower the averaged end-user ranking the more preferable the option.

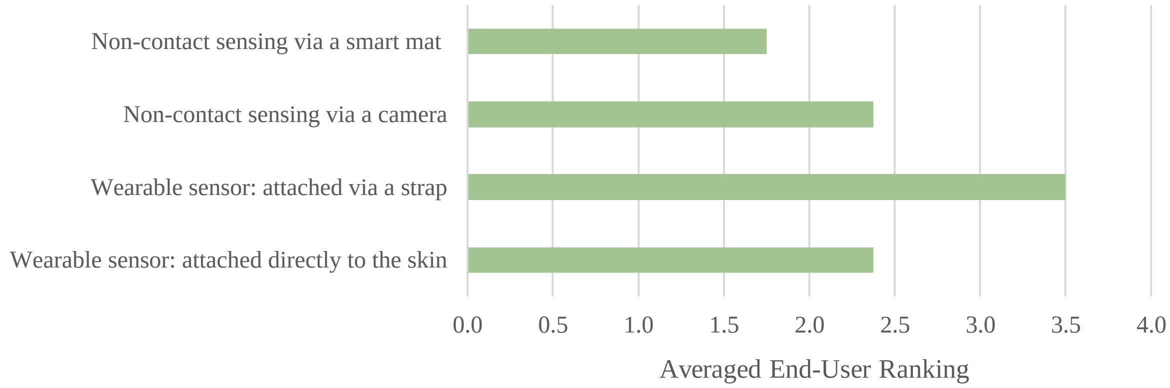

Figure 20: Question 3 Please number the following body position monitoring methods 1-4 in order of preference

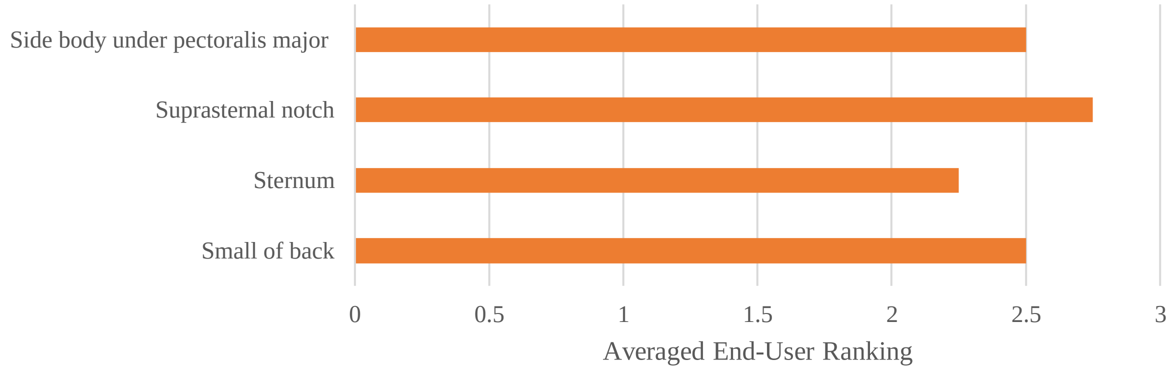

Figure 21: Question 4: Please number these attachment sites 1-4 in order of preference

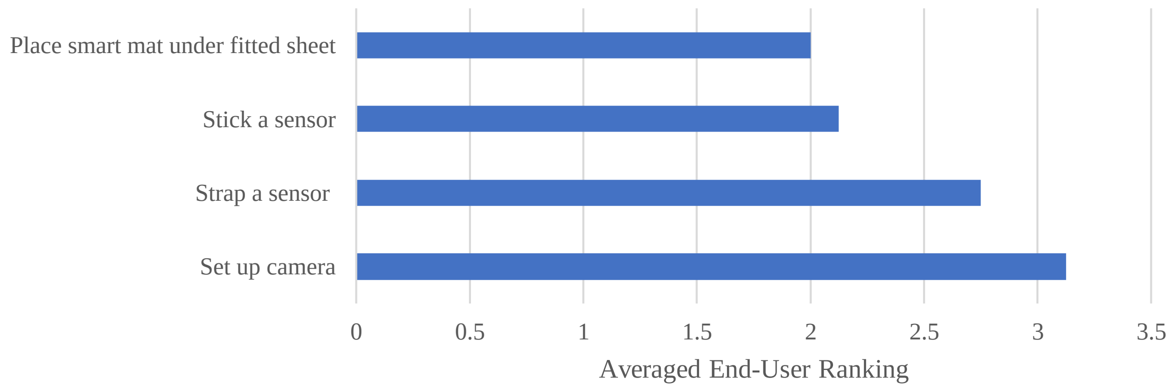

Figure 19: Question 5: Please number the following setup methods 1-4 in order of preference

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Appendix D: Customer Needs List

Table 2: Established customer requirements and associated sub-requirement definition, ranked in order of importance

Requirement	Sub Requirement	Sub Requirement Definition	Sub Requirement Ranked Based on Importance (1-23)
Harmless	Safe	The device does not cause any pain to the user	2
		Any heat dissipation in the device is separated from the skin of the user	
	Contained	All device components are contained and properly attached	17
Comfort	Shape	The device fits with the shape of the body region of attachment	11
		The device is ergonomic to attach and remove	
	Unobtrusive	The device permits natural body movements during sleep	3
		The device does not cause any discomfort	
		No external wires are attached to the device	
	Temperature	The device does not exceed an uncomfortable temperature	12
	Adaptable	The device can be used on all users regardless of their shape or size	13
	Weight	The device is lightweight	14
	Size	The device is small	15
	Noise	The device operates quietly	16
Durability	Resistance	The device is durable to knocks and drops	18
		The device does not lose calibration if knocked during sleep	
		The device is resistant to external factors such as body perspiration	
	Simplicity	The device is easy to use – minimal number of steps to set up	4
		The device is portable	
		The user or sleep health expert does not need to interact with the device once in use	

Usability		Device is easy to remove	
		The user or sleep health expert can interact with the device in an intuitive way	
	Efficiency	The device is able provide real-time feedback to the sleep health expert if required	19
		The device can record, as a minimum, a full night of data without being attached to power supply	
	Interpretability	Recorded data is easy to interpret	5
		If the device is attached in different orientations between patients the data presented is still easy to interpret	
Perception & Acceptance	Engagement	The device is appealing to the user and does not interfere with their perception of possible sleeping positions	20
	Satisfaction	Users and sleep health experts are satisfied with the device	1
	Privacy	The device does not breech users' privacy	6
Reliability	Effectiveness	The device fulfills the function of accurately identifying the four main body positions of supine, prone, left and right lateral, during sleep	7
	Precision	The device can accurately identify, as a minimum, the four main sleep positions of supine, prone, left and right lateral	8
	Functionality	The device as a whole system and its subsystems functions correctly	9
	Calibration	The device does not regularly lose calibration	10
Longevity	Long-term use	The device has a long lifespan	23
Manufacturing	Sustainability	The device is designed environmentally conscious	22
Affordability	Cost	The device is affordable	21

Return 1

Return 2

Appendix E: House of Quality

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Level of potential harm according to TGA																							
# of components exposed	+																						
Dimensions		+																					
# of identifiable body positions																							
# of parts		+	+	+																			
Temerature	+	+	+																				
Weight			+		+																		
Noise level																							
Durable - drop height device can withstand					-		+																
Water resistance		-																					
# of steps for use				+	+																		
# of steps to calibrate				++	+						++												
# of steps to cease use					+																		
Time without user interaction											+												
Storage space				+	+									+									
Battery life							+							+	-								
Time to process data				++						-		--			+								
Uncertainty of body position measurement				--								--											
User comfort rating / 10		--	--		-		--	--			+		--	++		+							
# natural body movements achievable			-		+	--	--							+					++				
Longevity					-	-			++	++						+							
Carbon footprint					+											+					+		
Cost			+	+	++		+		++	++	--	--	-	+	+	++	--	--	+	+	+	-	

			Design Requirements																						
		Unit	Rating	Count	mm^3	Count	Count	Degrees Celcius	g	dB	m	Time	Count	Count	Count	Hours	GB	mAH	Seconds	degrees	Score	Count	Years	kgCO2	$AUD
		Goal	↓	↓	↓	↑	↓	↓	↓	↓	↑	↑	↓	↓	↓	↑	↑	↑	↓	↓	↑	↑	↑	↓	↓
Customer Requirements	**Importance (%)**	**Who wants it (E-expert, U- end-user)**	Level of potential harm according to TGA	# of components exposed	Dimensions	# of identifiable body positions	# of parts	Temperature	Weight	Noise level	Durable - drop height device can withstand	Water resistance	# of steps for use	# to calibrate	# of steps to cease use	Time without user interaction	Storage space	Battery life	Time to process data	Uncertainty of body position measurement	User comfort rating / 10	# natural body movements acheivevable	Longevity	Carbon footprint	Cost
The device is safe to operate	9	E/U	Θ				○			Δ						○					Θ	Δ	Δ	Δ	Δ
All device components are contained	6	U	○	Θ	Δ		Δ	Δ					Δ				Θ				Θ				
The device is a werable friendly size	4	U			Θ	Δ			○				Δ				○	○	○		Δ				
The device permits natural body movements during sleep	8	E/U		Δ	○	○	Δ		○											Δ					
The device is unobtrusive with no external wires attached	6	U	Δ	Δ	Δ		Δ									Δ				Δ					
Device does not exceed an uncomfortable temperature	7	U	○					Θ					Δ							Δ					
The device is lightweight	4	E/U	○				Δ		Θ																
The device operates quietly	4	E/U								Θ		Θ													
The device operates quietly	4	E/U								Θ		Θ													
The device is durable to knocks and drops	2	E/U		Δ			Δ				Θ			Θ	Θ					○					
The device is resistant to external factors such as body persperation	3	E/U		Δ			Δ					○								Δ		Δ	Δ	Δ	Δ
The device is easy to use	5	E/U			Δ				Δ								Δ			Δ					
The device is easy to remove	4	E/U			Δ				Δ		Θ	Θ	○	○	○							○	○	○	○
The device does not require interction once in use	5	E/U		○									Δ	Δ	Δ					Δ					
The device is able to record as a minimum as full night of data	3	E				Δ																			
The deivce is energy efficient	2	E/U				Δ																			
Data is easy to interpret	6	E				Θ					Δ											Θ	Θ	Θ	Θ
Device is appealing	2	E/U							○	○	○	○													
Device does not breech users privacy	4	U									○	○	Δ	○	○					Θ					
Device fulfills function of accurately identifying as a minimum 4 body	7	E/U				Θ	Δ						○	Θ	Θ			Δ		○					
The device has reliable function	6	E/U				○	Δ														Θ				
The device has a long lifespam	1	E/U					○											Θ			○				
The device is designed environmentally conscious	1	E/U		Δ			Δ						○			Θ		○	○						
The device is cost efficeint	1	E/U					○																		
	100																								
Values			138	89	81	168	76	69	87	51	18	34	51	114	36	60	33	42	60	54	106	102	24	66	45
Importance			8.60%	5.55%	5.05%	10.47%	4.74%	4.30%	5.42%	3.18%	1.12%	2.12%	3.18%	7.11%	2.24%	3.74%	2.06%	2.62%	3.74%	3.37%	6.61%	6.36%	1.50%	4.11%	2.81%
Design Target			Class I	2	30	4	10	20	10	20	2	15	5	3	2	12	2	235	5	10	10	∞	5	1.76	100

Total
1604
100.00%

Competitor Comparison	Wearable Accelerometers	Smart Phone Accelerometry	Smart Mat	Cameras	Non-Contact Sensing
The device is safe to operate	5	5	4	5	5
All device components are contained	5	4	4	5	5
The device is a werable friendly size	3	2	3	2	4
The device permits natural body movements during sleep	3	3	5	5	5
The device is unobtrusive with no external wires attached	3	4	5	5	5
Device does not exceed an uncomfortable temperature	5	4	5	5	5
The device is lightweight	4	3	2	4	4
The device operates quietly	5	5	5	5	5
The device operates quietly	5	2	4	2	3
The device is durable to knocks and drops	4	4	4	5	5
The device is resistant to external factors such as body persperation	3	3	3	2	3
The device is easy to use	5	4	3	3	4
The device is easy to remove	3	4	5	5	5
The device does not require interction once in use	4	4	5	5	5
The device is able to record as a minimum as full night of data	5	4	4	4	4
The deivce is energy efficient	2	3	5	5	3
Data is easy to interpret	4	3	4	1	5
Device is appealing	5	5	5	1	5
Device does not breech users privacy	3	5	4	5	3
Device fulfills function of accurately identifying as a minimum 4 body	3	4	5	4	3
The device has reliable function	5	5	5	5	5
The device has a long lifespam	3	3	3	3	3
The device is designed environmentally conscious	4	4	2	3	3
Total	91	87	94	89	97
Average	3.96	3.78	4.09	3.87	4.22

Relationship	Scale
Strong	Θ = 9
Medium	○ = 3
Weak	Δ = 1

Appendix F: Double Diamond Design Process

The project followed the design process and Chapter 4 details how the project followed the second diamond (Figure 22) (Nessler, 2018).

Figure removed due to copyright restriction

Figure 22: Double Diamond Design Process Framework (Nessler, 2018)

Return

Appendix G: Summary of Main technologies

Table 3: Main technologies identified in the literature and their ability to meet the criterion of widely used, broad research area, identify main sleeping positions, require complex signal process and training. General comments are also made based on Chapter 1 and 2 findings. A ✓ indicates the technology meets the criteria and ✗ indicates it has not.

Technology	**Widely used**	**Broad research area**	**Able to identify as a minimum 4 main sleeping positions**	**Complex signal processing and machine learning**	**Comments**
Accelerometer	✓	✓	✓	✓	Majority of research explores strapping to the chest and the comfort surrounding this. There is little research on adhering the sensor directly to the skin. Papers also highlight the noisy signals of accelerometers and challenges of data interpretation with respect to orientation and sensor movement.
Smart Phone	✗	✗	✓	✓	Research explores phones strapped to the body; this is a large device to use as a wearable.
Smart Mat	✓	✓	✓	✓	There are multiple size smart mats explored, the trade-off between size and accuracy is important

					to note. These systems found increased accuracy with training personalised classification algorithms.
Camera system	✓	✓	✓	✓	Issues surrounding user privacy as well as obstruction of blankets. In addition, the set up around these systems is not ideal for at home use.
Non-contact sensing	✗	✗	✓	✓	There is more recent research surrounding non-contact methods of sensing, relying on other physiological signals. Again, this is a growing area and systems required personalised training for improved accuracy. There is also the consideration of how these methods will only measure the subject of interest in the case of more than one person sleeping in the room.

Return

Appendix H: Average sternal angle

The average angle is measured relative to the facet (Figure 23) .
https://teachmeanatomy.info/wp-content/uploads/Articulations-and-Parts-of-the-Sternum.jpg
Return

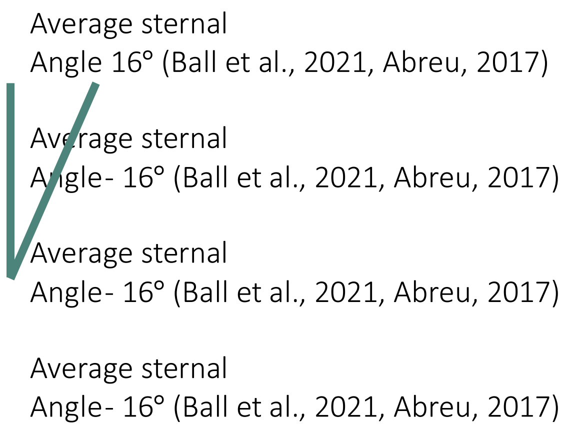

Figure removed due to copyright restriction

Figure 23: Average sternal angle is measured relative to the facet

Appendix I: Mega2560 Digital Pin HIGH and LOW Calculations

Calculation of ‘LOW’ and ‘HIGH’ bounds based on Mega2560 specifications.

Low reading: $0.3V_{cc}$

$V_{cc} = power\ input\ through\ the\ common\ rivet\ to\ the\ liquid = \ 5V$

$\therefore 0.3(5) = 1.5V$

High reading: $0.6V_{cc}$

$V_{cc} = power\ input\ through\ the\ common\ rivet\ to\ the\ liquid = \ 5V$

$\therefore 0.6(5) = 3V$

Return

Appendix J: Circuit Attached to Each of the Pins

The following calculation was completed for the voltage divider circuit to ensure a 'HIGH' (3V) reading is achieved when the sensor pin is in liquid.

$$V_{out@MCU} = V_{cc}\left[\frac{R2}{R1+R2}\right]$$

Rearrange equation to determine the value of R_2:

$$R2 = \frac{V_{out} \cdot R_1}{V_{cc} - V_{out}}$$

$V_{in} = 5V$

$V_{out} = 3V$

$R1 = 6M\Omega$ (Corresponds to the resistance of the sensor)

$$\therefore R2 = \frac{V_{out} \cdot R1}{V_{in} - V_{out}} = \frac{3V(6\times10^{6}M\Omega)}{5V - 3V} = 9M\Omega$$

Therefore, the selected value for R2 in the voltage circuit was $10M\Omega$ (Figure 24).

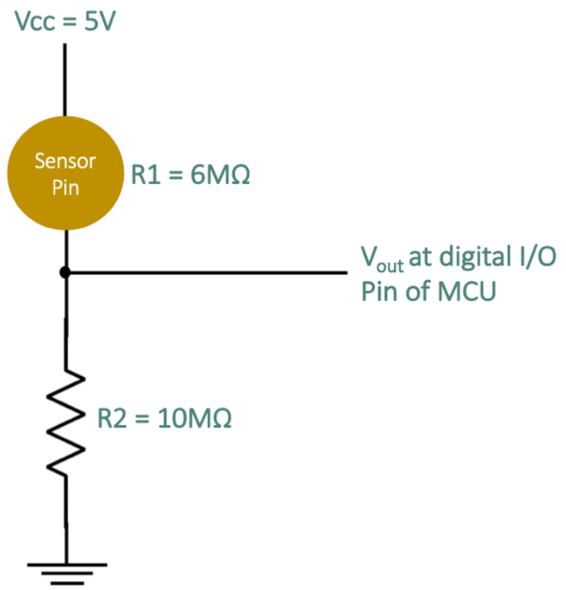

Figure 24: Voltage divider circuit connected to each pin

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Appendix K: Longitudes and Latitudes Assigned to Each in in Iteration One and Pin Arrangement

Latitudes 1 and 7 contained 1 pin, latitudes 2 and 6 contained 6 pins, latitudes 3 and 5 contained 12 pins and latitude 4 contained 16 pins (Figure 25). The pins in latitudes are 2 and 6 are 7.85mm apart, the pins in latitudes 3 and 5 are 6.81mm apart and the pins in latitude 4 are 5.89mm apart. Pins are labelled clockwise and with the corresponding longitudes and latitudes seen in Table 4.

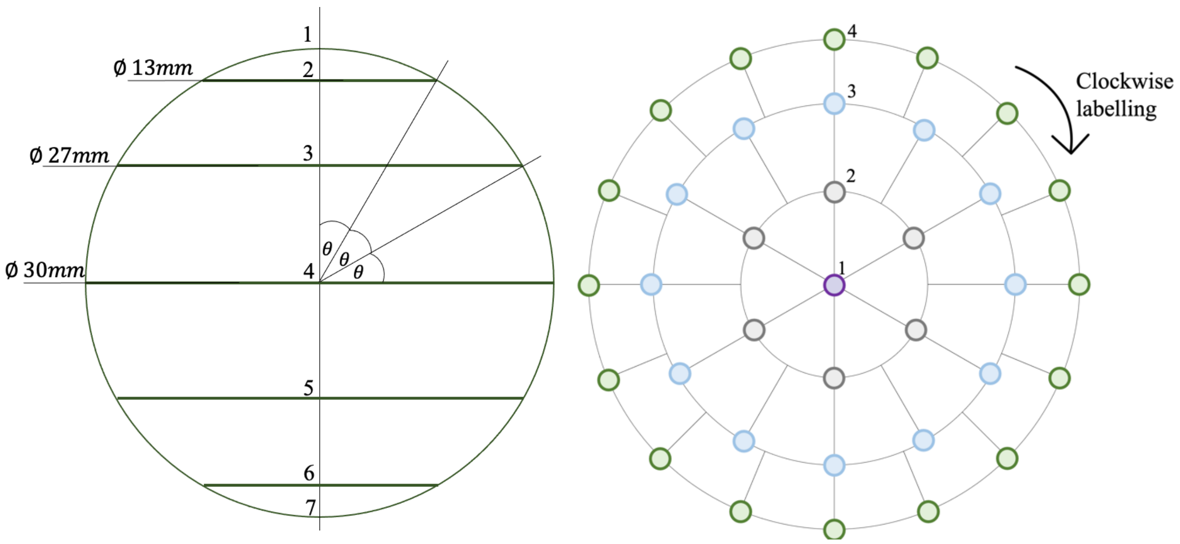

Figure 25: Left: Side view of spherical sensor - latitude lines labelled, theta (***θ***) is 30°. Right: Top view of top hemisphere – latitudes 1, 2, and 3 are mirrored on the bottom hemisphere.

Table 4*:* Pin number and corresponding latitude and longitude. Cells highlighted in green, blue and yellow correspond to pins in latitude lines 4, 3 and 5 respectively. Grey, orange, purple and pink correspond to pins in latitude lines 2, 6, 1 and 7 respectively. Format: Pin # (latitude (°), longitude(°))

1 (0,0)	15 (0, -45)	29 (-30, 0)	43 (60, 120)
2 (0, 22.5)	16 (0, -22.5)	30 (-30, 30)	44 (60, 180)
3 (0, 45)	17 (30, 0)	31 (-30, 60)	45 (60, -120)
4 (0, 67.5)	18 (30, 30)	32 (-30, 90)	46 (60, -60)
5 (0, 90)	19 (30, 60)	33 (-30, 120)	47 (-60, 0)
6 (0, 112.5)	20 (30, 90)	34 (-30, 150)	48 (-60, 60)
7 (0, 135)	21 (30, 120)	35 (-30, 180)	49 (-60, 120)
8 (0, 157.5)	22 (30, 150)	36 (-30, -150)	50 (-60, 180)

9 (0, 180)	23 (30, 180)	37 (-30, -120)	51 (-60, -120)
10 (0, -157.5)	24 (30, -150)	38 (-30, -90)	52 (-60, -60)
11 (0, -135)	25 (30, -120)	39 (-30, -60)	53 (90, 90)
12 (0, 112.5)	26 (30, -90)	40 (-30, -30)	54 (-90, 90)
13 (0, -90)	27 (30, -60)	41 (60, 0)	
14 (0, -67.5)	28 (30, -30)	42 (60, 60)	

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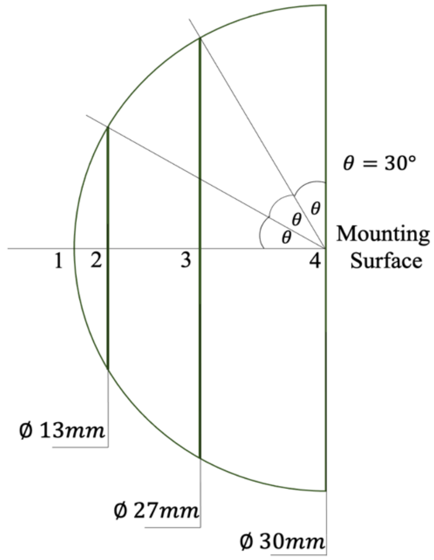
Appendix L: Iteration Two – the hemisphere



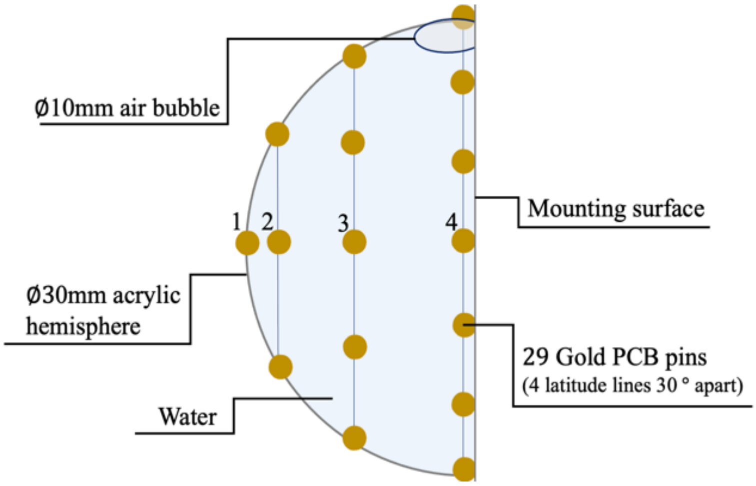


Figure 26: **Left:** Latitude lines of iteration two. **Right:** Final form of iteration two

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Appendix M: Iteration Three Pin Positions

Table 5: Pin position in iteration three. Pink, yellow, blue and green correspond to latitude lines 1, 2, 3 and 4 respectively.

Format: Pin # (latitude (°), longitude(°))

1(0,0)	5 (30, 240)	4 (60, 144)	9 (60, 324)	4 (90, 90)	9 (90, 240)
1(30, 0)	6 (30, 300)	5 (60, 180)	10 (60, 330)	5 (90, 120)	10 (90, 270)
2 (30, 60)	1 (60, 36)	6 (60, 216)	1 (90, 0)	6 (90, 150)	11 (90, 300)
3 (30, 120)	2 (60, 72)	7 (60, 252)	2 (90, 30)	7 (90, 180)	12 (90, 330)
4 (30, 180)	3 (60, 108)	8 (60, 288)	3 (90, 60)	8 (90, 210)	

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Appendix N: Flowcharts outlining the steps of the program on each of the MCUs

MCUs on the wearable part of the sensor:

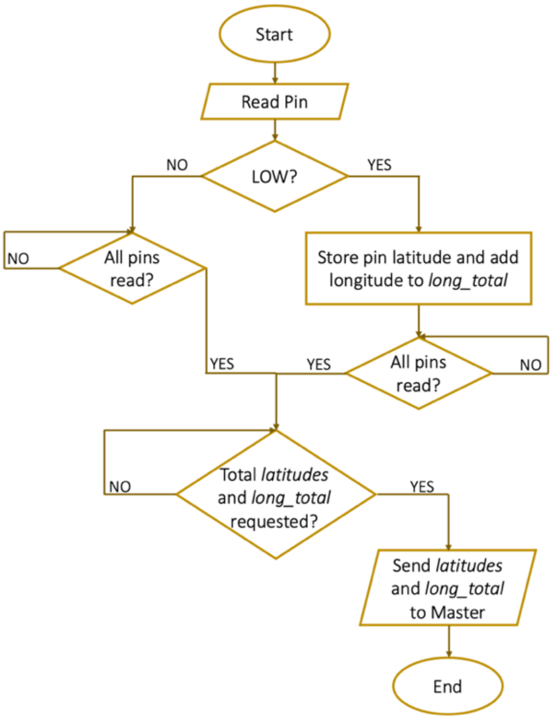

Figure 27: Flowchart outlining program completed on the Slave MCU

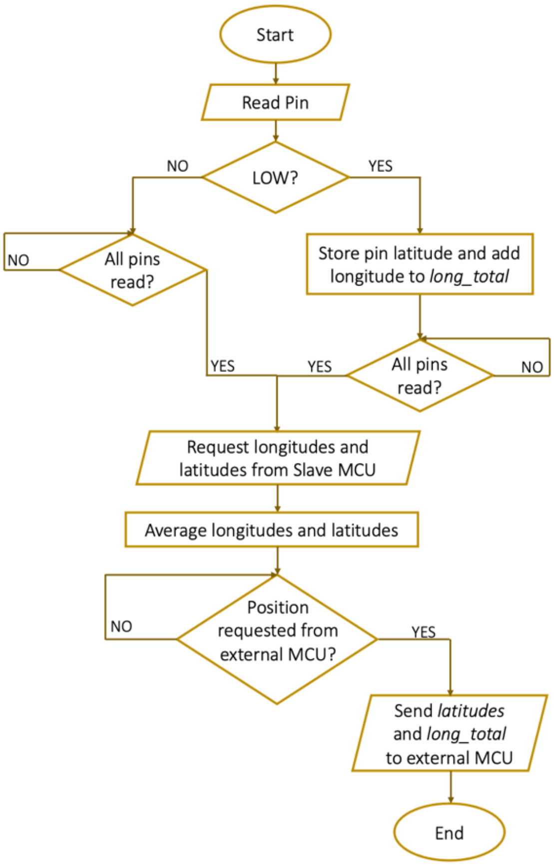

Figure 28: Flowchart outlining the program completed on the Master MCU

External MCU:

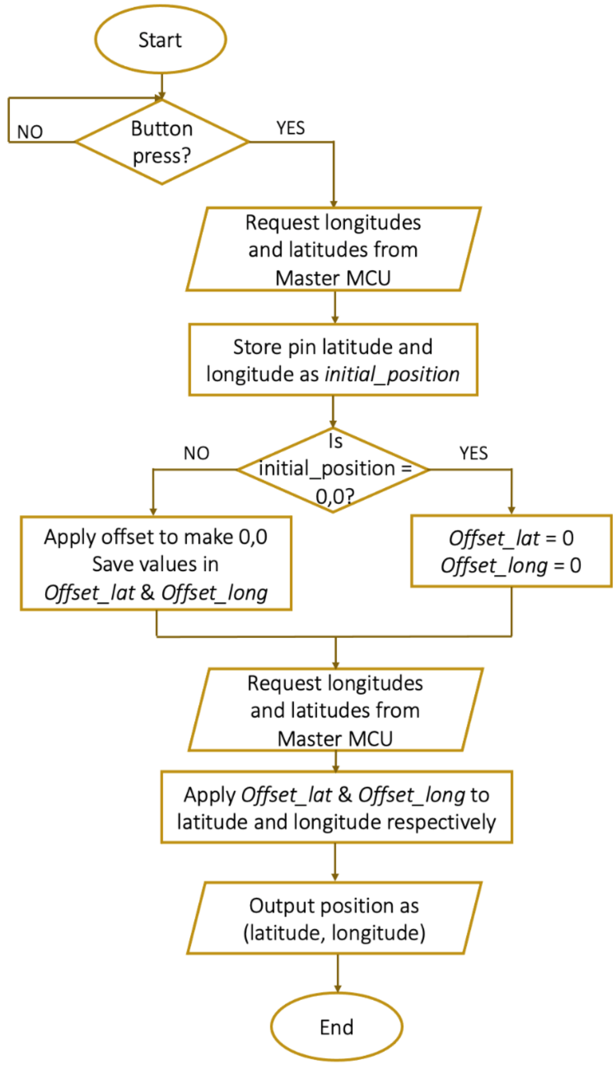

Figure 29: Flowchart outlining the program completed on the external MCU

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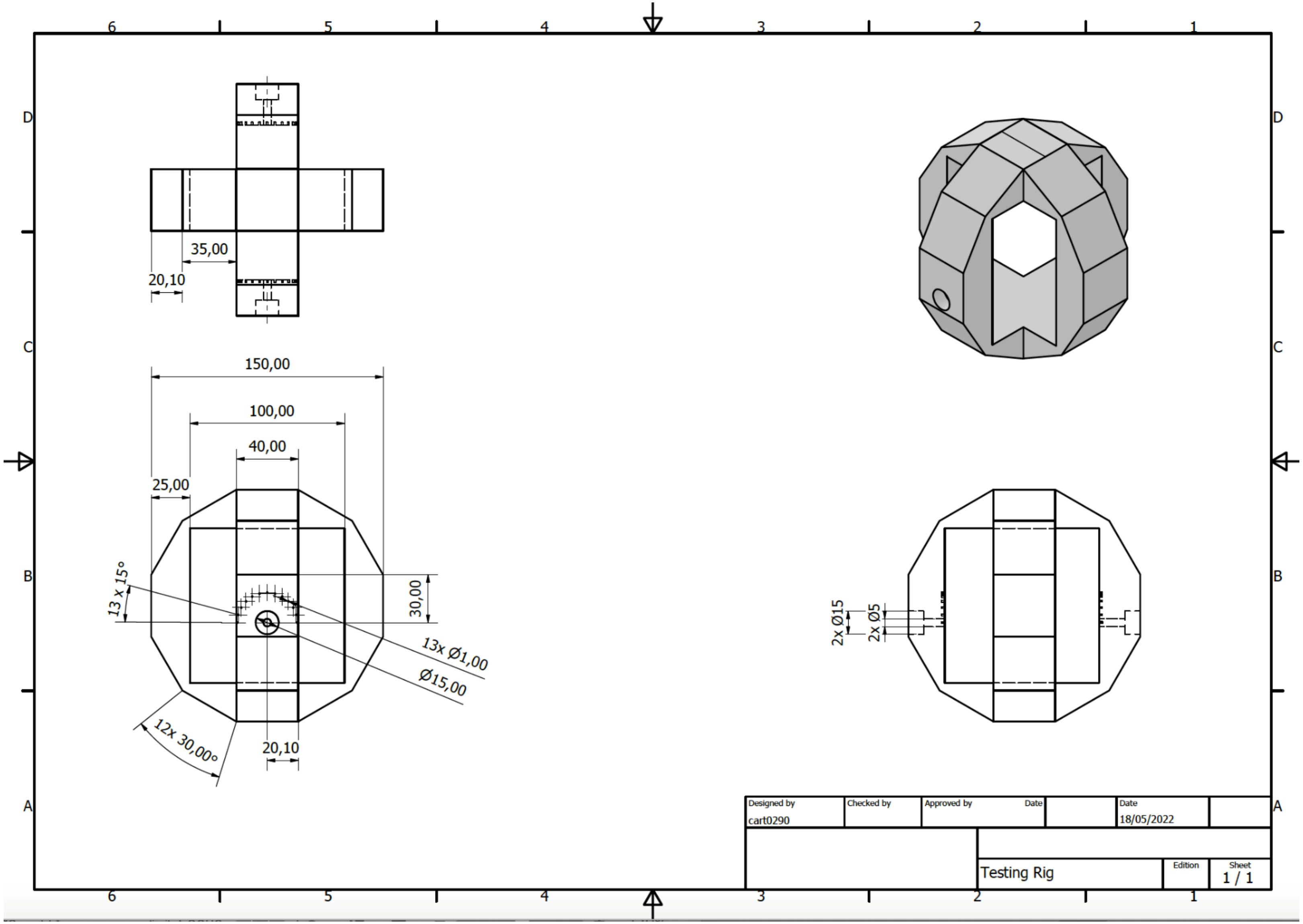
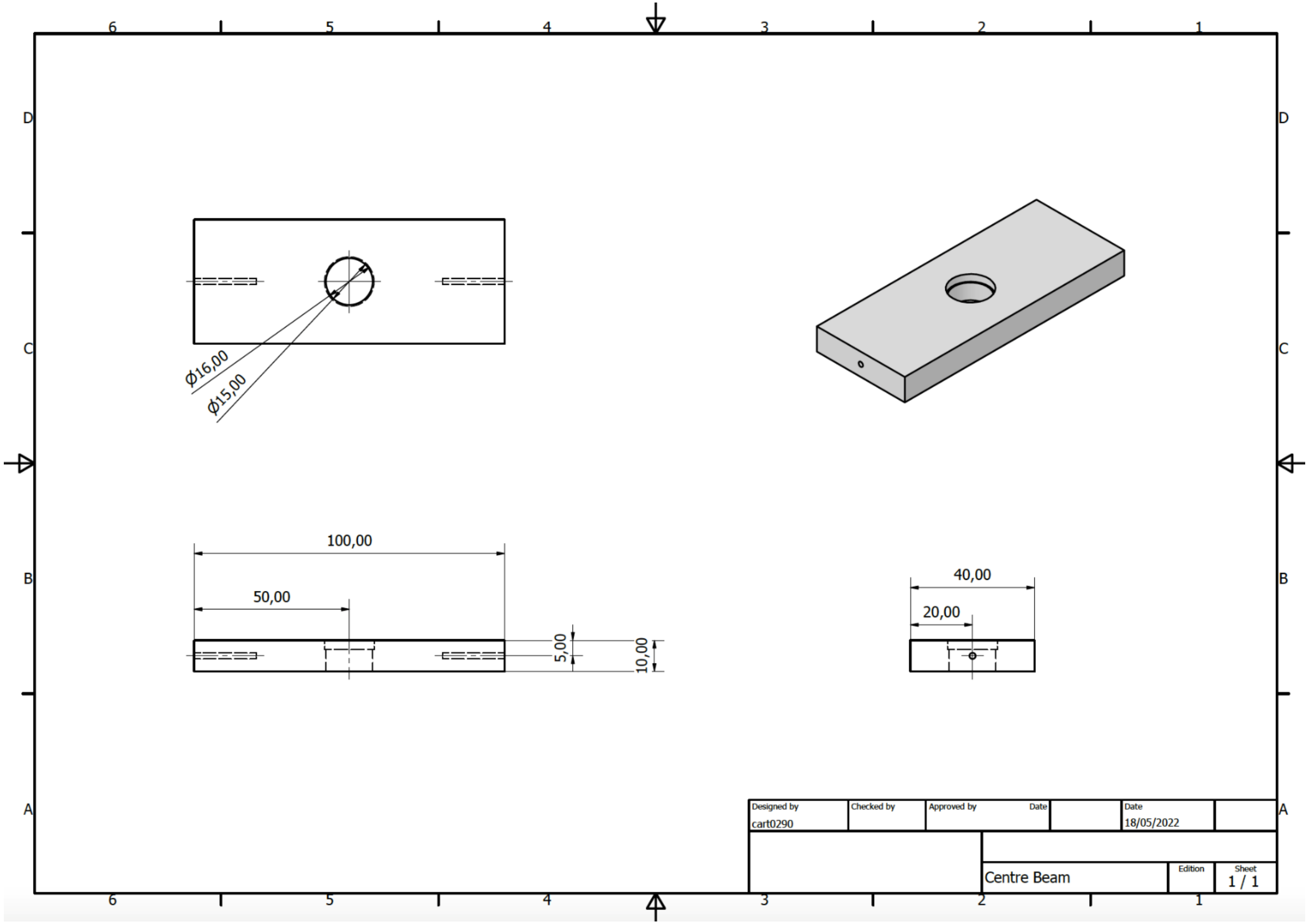
Appendix O: Engineering Drawing of Custom Testing Rig and Centre Beam

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