UNIVERSITY OF TWENTE.

Bachelor Thesis

Creative Technology

Developing a Smart Dog Collar for Enhanced Canine Welfare

Maximilian Haverkämper

Supervisor: Dr. Le Viet Duc, University of Twente

Critical Observer: Prof. Dr. P.J.M Havinga, University of Twente

University of Twente
Drienerlolaan 5
7522 NB Enschede
Netherlands

Abstract

Applying technology for monitoring and tracking is not only integrated into many products and part of numerous research but can also increase the welfare of living beings. This study aims to develop the hardware for a Smart Dog Collar which creates a minimum intrusiveness to the dog while offering meaningful functionality like vital and environmental data recording to increase canine welfare. Through a combination of background research, ideation, prototyping, and evaluation, the study explores the considerations and constraints associated with the development of such a smart collar.

A concept is described which includes location tracking, ambient temperature measurement, physical activity tracking and heart rate measurement. This concept is taken into a partly functional prototype which can measure the environment temperature, utilizes GPS for location tracking and an inertial measurement (IMU) for physical activity tracking while still being small and lightweight. Additionally, the heart rate recording through a PPG sensor was being implemented into the prototype which showed that this type of sensor is not accurate when measuring at the dog’s neck. The challenge for the design was the fitting of all hardware in a small casing that can be part of a collar which is not annoying or intrusive to the dog while it is wearing it. By setting up the appropriate specifications, selecting the most suitable hardware and designing the housing precisely, this challenge was overcome.

This work contributes to the development of smart dog collars by prioritizing animal intrusiveness, comfort, and effectiveness of the monitoring and tracking features. By addressing the identified limitations and optimizing the collar design, this research can contribute to the development of a Smart Dog Collar that improves the welfare of dogs.

Acknowledgement

I am especially grateful to my supervisor Dr. Le Viet Duc. His insights, constructive feedback, and support have been a great help in shaping this thesis. Additionally, I would like to express my special thanks to Filipe Serra Bragança for giving me great support, help and veterinary insights.

I also express my graditude to the people who participated in the user testing. Their willingness to dedicate time and provide valuable insights and feedback has significantly enriched the quality of my research.

Lastly, I would like to thank my family for their support which have kept my motivation high and gave me the energy I needed during the process of the graduation project.

Table of Contents

....1

CHAPTER 1 – INTRODUCTION 7

1.1 Research Questions 7

CHAPTER 2 – BACKGROUND RESEARCH 8

2.1 Literature Review 8

2.1.1 Functionalities *8*

2.1.2 Technology *10*

2.1.3 The design *11*

2.1.4 Conclusion of the Literature Review *11*

2.1.5 Discussion of the Literature Review *12*

2.2 State of the art 12

2.2.1 Overview of the Smart Dog Collar Market and Products *12*

2.2.1 Summary of the State of the Art *16*

2.2.2 Flaws and possible Solution *17*

CHAPTER 3 – METHODS AND TECHNIQUES 19

CHAPTER 4 – IDEATION 21

4.1 Stakeholder Identification and Analysis 21

4.2 Additional Research 22

4.2.1 Lameness in dogs *22*

4.2.2 heart rate recording technology *23*

4.2.3 Design and Design Specifications research *25*

4.3 Identification of Meaningful Functionality 25

4.4 Identification of the Concept's Functionalities 26

4.5 Concept 27

CHAPTER 5 – SPECIFICATION 28

5.1 Requirements 28

5.1.2 Functional Requirements *28*

5.1.3 Non-Functional Requirements *28*

5.1.4 Requirement Prioritization *29*

5.2 Hardware Specification 30

5.3 Design Iteration and Specification 32

CHAPTER 6 – REALISATION 34

6.1 Component selection 34

6.1.1 The material for the 3D printed casing *34*
6.1.2 The microcontroller *34*
6.1.3 GPS Module *35*
6.1.4 Temperature Sensor *35*
6.1.5 PPG-Sensor *36*
6.1.6 Battery *37*
6.1.7 SD Card reader *37*
6.1.8 Collar *37*
6.2 SOFTWARE AND CIRCUIT 38
6.2.1 Circuit of the System *38*
6.2.2 Software *39*
6.2.3 Data storage *39*
6.2.4 Bluetooth Connectivity *40*
6.3 DESIGN 41
6.3.1 Design of the Main Case *41*
6.3.2 Design of the Heart Rate Sensor Casing *43*
6.4 ASSEMBLY PROCESS 44
CHAPTER 7 – EVALUATION 45
7.1 USER TEST PROCEDURE 45
7.2 EVALUATION RESULTS 48
7.2.1 Design *48*
7.2.2 Hardware Evaluation: *48*
7.2.3 Conclusion of Design and Hardware evaluation *50*
7.2.3 Evaluation of the Functionality *51*
7.2.4 Results of Functionality Evaluation *57*
7.3 REQUIREMENT EVALUATION: 58
CHAPTER 8 – DISCUSSION & FUTURE WORK 60
8.1 DISCUSSION 60
8.2 FUTURE WORK 61
CHAPTER 9 – CONCLUSION 63
REFERENCES 64
APPENDIX 67

Chapter 1 – Introduction

The healthcare sector is an important area in which it has been used to prevent, diagnose, and treat a wide range of health issues. As one part of it, wearables offer the functionality of activity and health tracking and can improve the overall health and fitness of the user. Products such as Galaxy Watches, Apple Watches, Google Pixel Watches and Fitbit Watches are able to record activity level, heart rate, blood oxygen level and record ECGs for humans. In order to bring this advancement also to other species, wearables for dogs are being developed more and more lately [1]. One reason for this is the difficulty for dog owners to monitor their dog's welfare and activity level. It is found that dog activity trackers increase the caregiving and the motivation of the owner to increase physical activity together with the dog [2]. This could, only being one use case, detect too less activity of dogs and therefore tackle the problem of obesity which lead to several health issues and can be cured by increasing physical activity [3]. In addition, statistics [4] indicate that the number of dogs in Europe is growing, and the Survey of the Veterinary Profession in Europe (FVE) stated in 2019 that "More veterinarians will be needed for working with companion animals in the next 5 years" [5, p. 95].

Developing such a smart collar to track the activity, track the geolocation, measure environmental data and vital signs of the dog not only enables owners to monitor animal welfare but also gives the chance to increase it. This smart collar makes it possible to detect diseases in dogs much earlier which makes the treatment easier, cheaper and reduces the workload on the healthcare system.

1.1 Research Questions

The aim of the research is to develop a concept for a smart collar for dogs. A key point of attention is to identify the right functionalities that support the dog's welfare and how to implement them. Another focus of the research is to design the concept with a minimum of intrusiveness and comfortable wear. To meet this requirement, the following research question is derived:

How to design a smart collar for dogs that has minimum intrusiveness and meaningful functionality for monitoring and tracking?

More specifically, the main question is divided into the following sub-research questions:

- **What are meaningful functions of smart dog collars?**
- **What are the suitable technologies to obtain the meaningful functionality?**
- **How to integrate sensors for minimum intrusiveness into a smart collar?**
- **How to design the protocols for testing and evaluating of the smart collar?**

Chapter 2 – Background Research

Sine it is necessary to obtain background information before the ideation and specification of the prototype can start, this chapter contains a literature review to obtain an overview about the research about wearables for dogs, the state of the art of smart dog collars and additional research.

2.1 Literature Review

In order to develop a concept of a smart dog wearable that has meaningful functionality and provides minimal intrusiveness to the dog, an overview of existing literature in terms of different functionalities, technologies and design approaches of dog wearables is needed. Therefore, the main goal of the literature review is to get an overview of research containing concepts of smart wearables for dogs and discover their functions, design approaches, and technological implementation to answer the question: *What are the functionalities and technologies implemented into smart wearables for dogs and what design approach is applicable to use when developing such a system for dogs?*

2.1.1 Functionalities

One area of functionalities of dog wearables that was embedded in most of the concepts is the recording and tracking of medical data. The developed products from Sec et al. [6], Lin et al. [7], Almazan et al. [8], Khatate et al. [9], Brugarolas et al. [10], and Patil et al. [11] are all capable to record the heart rate of the dog. In addition, the concept developed by Brugarolas et al. [10] and Lin et al. [7] share the possibility of recording the heart rate and its variability as well. The research from Sec et a. [6] implemented heart rate measurement together with the detection of breath frequency to give the system the possibility to detect an epileptic seizure. Another project that also uses the functionality of tracking and recording the heart rate, heart rate variability and respiratory rate (Breath frequency) uses the data for "identifying physiological correlations to stress, distress, excitement, and other emotional states" [10, p. 1]. Furthermore, Patil et al. [11] developed a system, which monitors the temperature, humidity, and heart rate, giving scientists a tool to research the correlation between the environment and the physical changes of the dog. Another medical function, the measurement of blood pressure, was integrated into a wearable for dogs by Khatate et al. [9]. In summary, heart rate and variability measurement, blood pressure measurement, epileptic seizure detection, and respiratory rate measurement appear to be medically based functions implemented in the concepts for the canine wearables discussed in this review.

In addition to these medical functionalities, physical activity tracking provides an approach to tackle another health-related problem. An overview of activity data offers the owner a tool to detect too less activity and therefore reduces the risks of the occurrence of obesity in dogs [3]. Hammerla et al. [12] implemented activity tracking through the use of a system that is capable of detecting if the dog is in a forward motion. Additionally, another approach for measuring physical activity that has been found is to "track the number of steps the pet makes" [8, p. 418].

If the dog has run away, it is important to track its location in order to catch it more quickly and protect it from dangers such as a collision with a car. Zeager et al. [13] developed a vest for search and rescue (SAR) dogs so that human companions can easily track their location. The concept also includes a capacitive sensor that the dog can bite on and use to decide when to pass coordinates to a companion. Almazan et al. [8] use location recording in their dog wearable too, but it is implemented to give the owner a tool to track the dog in situations where he/she is not near the dog, or the dog has run away. In conclusion, these two functionalities are based on location technology but are different in their approach, which shows that location data can be a useful functionality for both owners of pet dogs and companions of working dogs.

The implementation of behaviour tracking in smart dog wearables can give an overview of the activities that the dog has done. The wearables developed and discussed by Hammerla et al. [12], Williams et al. [14] and Ahn et al. [15] have the functionality of behavioural detection of different states in which the dog is. Moreover, the product from Hammerla et al. [12] can recognize 16 different patterns like barking, chewing, digging, drinking, eating etc. This information can be of help to scientists who are researching the behaviour and psychology of dogs. In addition to the behaviour classification and detection, William et al. [14] implemented an ambient, temperature, noise and humidity sensor into a system which enables simultaneous data recording and a deeper understanding of how the dog interacts and is influenced by its environment. Overall, different dog behaviour can be tracked and, when combined with environmental data, correlations between those can be found, giving scientists the ability to understand dogs in a better way.

2.1.2 Technology

This subsection describes the finding of data transmission technologies such as WIFI, Bluetooth, and Zigbee, the use of sensors such as electrodes, IMUs for recording cardiac data, and GPS for location tracking.

There are different ways to ensure the data transfer between the wearable and a smartphone or computer. The data transfer between the phone or computer and the wearable itself is achieved using Bluetooth by Lin et al. [7], Zeagler et al. [13], Williams et al. [14] and Ahn et al. [15]. Khatate et al. [9] implemented Bluetooth for the direct transfer of data from wireless ECG electrodes to the main device which uses Zigbee to communicate with a PC. In addition, WIFI is implemented into the prototype by Brugarolas et al. [10] to connect with a computer that analyzes the data. For the functionality of accurate worldwide location tracking the Global Positioning System (GPS) can be used. Zeager et al. [13] and Williams et al. [14] used the GPS receiver of a smartphone that connects to the main system via Bluetooth for that matter. In the prototype of Zegeret al. [13] a waterproof smartphone has been used since it is attached to the vest itself. The wearable of Almazan et al. [8] contains a separate GPS receiver which is attached to the dog collar and connected to the main system.

When considering the medical functionality that contains the measurement of heart data of the dog two different technologies can be used. One method that has been used to obtain heart rate data by Lin et al. [7], Almazan et al. [8], Khatate et al. [9], Brugarolas et al. [10], and Patil et al. [11] is the measurement of electrical signals from the heart. Two electrodes in contact with the skin allow recording of the electrocardiogram (ECG) in these concepts. This ECG can provide data about the heart rate and the heart rate variability of the dog. The other approach that can achieve the same functionality is using an accelerometer together with a gyroscope barometer [6]. These two sensors record small vibrations generated by the heart and allow the recording of heart rate and respiratory rate during the dog's sleeping and waking states [6].

An IMU (Inertial measurement unit) embedded into the wearable can enable different functionalities of the system. Physical activity tracking was implemented by Almazan et al. [8] by using three-axial accelerometer data that contains certain patterns, especially ups and downs, that can be used for motion analysis. This analysis calculates the steps the dog has taken during the recording. In addition, the functionality of behavioural detection was obtained by using the same data in the prototype developed by Hammerla et al. [12] and Ahn et al. [15].

2.1.3 The design

Embedding the hardware onto or into a dog collar can provide comfort and minimal obstruction to the dog. Hammerla et al. [12], Sec et al. [6], Williams et al. [14] and Ahn et al. [15] selected a collar to attach all their sensors and hardware to. Hammerla et al. [12] state that a collar design has been chosen because the head movement of a dog is important for many different activities like drinking, barking and full body activities like walking or running. This design provides minimal obstruction to those and is comfortable for the dog to wear [12]. Williams et al. [14] and Ahn et al. [15] designed a casing for the hardware that you can attach to an existing collar. The type of wearable was chosen because “One advantage of the collar mechanical design is that the puppies are already socialized to wear collars. This comfortability ensures the system does not modify the natural behaviour intended to be measured.” [14, p. 4630]. To summarize, the collar-based design can offer minimal intrusiveness and obstruction to the dog and thus is suitable for wearables worn at all times or tracking the dog’s behaviour.

When requiring a wearable that has a higher weight a vest-based design is from purpose. For a wearable for Search and Rescue (SAR) dogs Zeagler et al. [13] used a Julius K9 power harness vest to attach the hardware to. He states that the vest offers a design with padding that decreases the pressure that is taken to the dog's spine. So, the vest design shows a way to reduce the load on the dog's spine at high weights, which can be necessary for working dogs like SAR ones that wear heavy gear temporarily.

When building a low-fi prototype regular dog clothing can make it easy to test the hardware that should be evaluated. The concept of Lin et al. [7] shows a design in which the hardware can be stored under regular dog clothing. That increases the combability of the product with different sizes of dogs and makes it easier to evaluate a low-fi prototype.

2.1.4 Conclusion of the Literature Review

This review aimed to get an overview of the functionality, their technologies, and the way of designing smart dog wearables. The first category of functionalities discovered, the vital sign recording includes heart rate recording, heart rate variability recording, respiration rate measurement, epileptic seizure detection, and respiration rate monitoring. The heart rate and heart rate variability can be recorded using electrodes to record an ECG. Another approach to detecting the heart rate and also respiratory rate is using an accelerometer in combination with a gyroscope barometer to detect the movements of the heart. Another functionality of smart dog wearables is the physical activity tracking of the dog which can be implemented by using an IMU and its data for motion analysis. Furthermore, the functionality of location recording is implemented into two prototypes to determine the location of the own dog or to give Search and Rescue (SAR) dogs the possibility to share their own location using GPS technology. In addition, another functionality that has been used by dog wearables is the detection of different behaviour that the dog is performing. It is implemented into dog wearables to further understand the dog's behaviour and can be realized by using an IMU as well. All this recorded data needs to be sent to a computer or smartphone to be analyzed and displayed. To implement connectivity Bluetooth, WIFI and ZigBee were used by the prototypes that have been discussed in this review.

The design of a wearable for pet dogs should offer minimal intrusiveness and should be comfortable to wear. The literature showed that by using a collar-based design these specifications are met and that it is the best wearable type regarding these aspects. Another type of wearable discovered is the vest-based design that should be considered when the wearable has a heavy weight to decrease the load given to the dog's spine.

2.1.5 Discussion of the Literature Review

The overview revealed a lot of functionalities, technologies and two design approaches. For the implication for the graduation project, the result in terms of the design revealed useful information. A collar-based design will be chosen because of the advantages of minimal intrusiveness and comfort. In addition, the scope of the thesis is to develop a device that increases the well-being of the dog. Therefore, location tracking, for the case of the escape of the dog, electrodes to obtain the heart rate and heart rate variability data, and an IMU to be able to track physical activity are considered to be implemented into the prototype of the smart dog collar.

A limitation of this literature review is the large variety of different wearables and the lack of scientific papers and projects on this topic. Therefore, the goal and the research question of the review could not be formulated any more specifically.

2.2 State of the art

2.2.1 Overview of the Smart Dog Collar Market and Products

Several smart collars for dogs already offer a wide range of functionalities. In the following, an overview of these will be given.

Tractive

The smart collar Tractive DOG 4 developed by the company Tractive offers GPS tracking and monitors the activity and the sleep of the dog. The website of the product [16] shows that the device is waterproof to the IPX7 rating and the battery lasts 7 days. It uses LTE to communicate with the smartphone app that enables the owner to see the information, including the current location of the dog and it gives the owner a wellness score that is being calculated through the Activity and sleep data. The design of the Tractive DOG 4 makes it possible to mount it to any dog collar. The device has a weight of 35 grams [16].

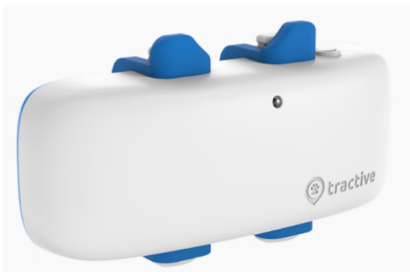

Figure 1: Tractive Dog 4 [16]

Fi

The company Fi currently sells the dog collar Fi Series 3. It comes in different styling options. The customer can decide between 8 different designs, and you can buy 57 different third-party collars that are compatible with the attachable module of Fi Series 3. Furthermore, if you buy the collar directly from Fi they are offering 5 different sizes. The GPS that is implemented uses four positioning satellite constellations that allow tracking the dog within a radius of 1,83 meters. LTE is being used for data connection to the app. The app enables setting up regular locations of the dog and the notification if the dog escapes those areas. The stainless-steel body is waterproofed by the standards of IP68 & IP66K which means the device is resistant to being 1.5 meter under water for 30 minutes and it is completely dust proof. This should withstand all usual doc activities since dogs are not diving under the water surface. Additionally, the device has a battery life of up to three months, which should ensure seamless data recording and usability. The weight of the Fi module itself is 36,86g. This information was found on the product website [17].

Figure 2: Fi Series 3 [17]

Whistle Health & GPS

The company Whistle offers a device that is called Health & GPS that can be mounted to any dog collar. Information on the website [18] revel the device uses GPS and LTE and processes these data using Ai technology and has sufficient water resistance of up to 2 meters for 60 minutes. In addition, it sends location alerts if the dog is leaving a designated area. The health monitoring analyzes the licking, scratching, drinking and sleep of the dog to detect potential health. In addition, the app displays the pet's burned calories, distance travelled and active minutes. The customer can also get in contact with a licensed Vet through chat, email or a video call. The device can be mounted to normal dog collars. Whistles product weighs about 34 grams [18].

Figure 3: Whistle Health & GPS [18]

Invoxia

The company Invoxia is currently developing a smart dog collar that is not being launched yet. The smart collar offers Heart rate monitoring, respiratory rate monitoring, activity and sleep monitoring and Real-time GPS tracking [19]. These functionalities lead to spotting early symptoms of severe heart disease and monitoring the efficiency of the dog's treatment. WPS, GPS, LTE and Bluetooth are implemented into the product [19].

Figure 4: Invoxia Smart Dog Collar [19]

PetPace 2.0

PetPace announced their product PetPace 2.0 [20] and it has been released in the month this research finished. It is a Smart Collar that offers a lot of different functionalities. Like the device from Invoxia, it is also capable of measuring heart data. It offers heart rate variability measurement and pulse monitoring. In addition, location tracking, activity tracking, calorie monitoring, sleep tracking, respiratory measurement and pain and stress tracking are part of the functionality of PetPace 2.0 [20].

Figure 5: PetPace 2.0 [20]

2.2.1 Summary of the State of the Art

Product	GPS	Activity monitoring	Heat measure	LTE	Sleep detection	Water resistance	Heart rate detection	Respiration rate detection
Tractive	x	x		x	x	x		
Fi	x	X		x	x	X		
Whistle Healh & GPS	x	x		x	x	X		
Invoxia	x	x		x	x	X	x	x
PetPace 2.0	x	x	x	x		X	x	x

Table 1: Overview of all smart collar's functionalities seperated by devices and technologies

Functionalities

All products offer tracking of the dog's location by using GPS technology. In order to send data that is collected by the collar to the mobile application the devices use the LTE wireless broadband communication technology which ensures data transmission in most areas. This is especially important for location tracking if the dog has run away. Another similarity between these products is the recording of the physical activity data of the dogs. This feature shows the owner if the dog has had enough exercise. It can be used on a daily basis to determine if the dog has had enough exercise or if it needs a walk or other physical activity. The product of Tractive can measure the ambient temperature. This functionality makes it possible to detect if the dog spends a lot of time in a very cold or warm environment where he might suffer from hypothermia or overheating. In addition, PetPace's product is able to measure the dog's internal temperature and categorize it as low, medium and high, which "offers significant value for preventive medicine for dogs or cats at risk of developing medical conditions associated with an abnormal temperature" [21, p.1]. Three of the products are able to detect the time the dog is sleeping. The Whistle product can detect scratching and licking of the dog, which often occurs when the dog is sick and thus provides a function to detect undetected diseases. The Invoxia and PetPace products have implemented the measurement of heart rate and respiration rate. Both products have been released during the time of this research.

Design

All the smart wearables for dogs that have been found are based on a dog collar design. Tractive and Whistle designed their products in a way that they can be attached to a normal dog collar. The wearable from Fi is also attachable but requires a special collar for the connection and acts as a link between two ends of an open collar. Tractive's design includes silicone elements that wrap around the collar and connect the device to the collar, while Whistle's product uses a metal frame for attachment. In difference to the overall system design, PetPace and Invoxia only sell complete collars with all the hardware integrated into them. Invoxia's collar is using "dermatologically compatible silicone, strap materials: RPET fabric (recycled and 100% recyclable polyester) and metal buckles" [19, Technical specifications]. One concern of these two collar designs is missing a point to connect a leash to. The websites, product information and pictures of the products do not reveal one. If you want to walk your dog while it is secured on a leash, you must either remove the smart collar or place a second one around its neck. The two companies do not state a reason for it, but it is considered that a leash attached to the collar could change the accuracy of the data that is recorded because of unnatural forces and movement of the collar.

Technology

All the products make use of GPS technology for location tracking and have LTE (Long-Term Evolution) for long-distance Data transfer via the mobile network integrated. One limitation of the technology research is that the companies do not reveal the exact components or technologies that they are using. An example is Inxoxia's description: "Using sensor fusion and state-of-the-art Artificial Intelligence algorithms, Heartprint Technology™ provides unique insights on your dog's health. It provides a geometrical representation of your dog's heartbeats." [19, p. 1]. This does not indicate whether they are using electrodes, inertial measurement units, or other hardware and technology to record heart-related data. One insight that Invoxia reveals in difference to all other products in Chapter 2.2.1 is the accuracy. The company states the respiratory rate measurement has an accuracy of 97% and the heart rate measurement has an accuracy of 99% [19].

2.2.2 Flaws and possible Solution

These smart dog collars offer pet owners a number of valuable features. Useful information regarding the design, technology and functionality have been gathered. However, one flaw of the products is the lack of transparency which leads to limitations. Particularly regarding the technology used for heart rate recording, the sleep detection and the algorithms for the physical activity tracking. This intransparency complicates or prevents the assessment of the overall accuracy and effectiveness of those.

Therefore, research is needed that has the potential to close the transparency gap and facilitate the implementation of these features and technologies so that they can be incorporated into future research and products. Doing so could lead to more affordable smart wearable technology for pets, which would benefit both pet owners and the well-being of their animals.

Chapter 3 – Methods and Techniques

The creative technology design process [22] is used to develop the concept for the smart dog collar, which is created for the Creative Technology Bachelor study at the University of Twente. This design process developed consists of 4 phases: the ideation phase (Ch. 4), the specification phase (Ch. 5), the realisation phase (Ch. 5) and the evaluation phase (Ch. 7).

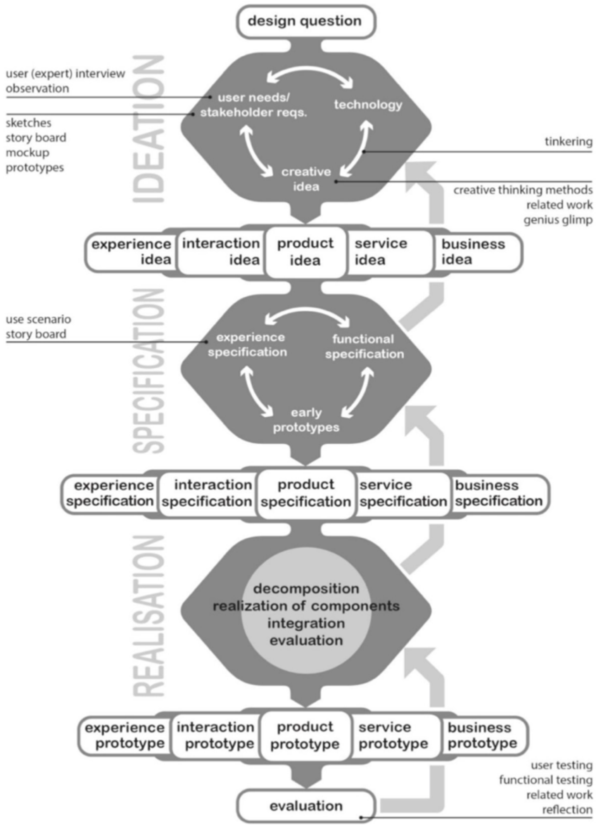

Figure 6: Creative Technology Design chart, the three phases of prototype development [22]

During the background research chapter 2, the functionality and design of the concept have been researched and important aspects have already been discovered. In the ideation phase the identification and analysis of the stakeholders for this project have been conducted to obtain an overview and to discover who can be considered regarding the scope, expert knowledge and could potentially participate in interviews or user tests. Furthermore, during an interview with a veterinarian possible functionality of the collar has been discussed and filtered. To obtain a broader expert opinion a survey about these functions have been created and experts have been asked to rate them.
Additional background research provided the necessary information to build the first concept that involved the design, the functionalities, and technologies.

During chapter 5, the specification chapter, the scope was to define requirements and specifications that lead the creation process of the concept prototype realization (Chapter 6). The requirements have been split into non-functional and functional ones to guide the design, development, and evaluation process of the product prototype by defining specific features as well as quality attributes that needed to be met. The prioritization and filtering of those have been conducted by using the MoSCoW method [23]. This method categorizes the requirements into four distinct categories and helped to manage the time and set certain borders to which extent the prototype will be developed. Additionally, specifications for the components were defined to be able to select the right hardware in terms of functionality, cost and benefit. Moreover, first virtual 3D prototype for the design was created and the results discussed.

In Chapter 6, the realization chapter, the requirements, specification and insights of the previous chapter have been transformed into a working concept. To achieve this first all the hardware has been selected by closely stick to the predefined requirements. After it the design was conceptualized and build by considering the requirements and dimensions of the hardware. The 3D file was created by using the Software Autodesk Fusion 360 and the design printed with by a Formlabs Form 3L 3D printer. Next a circuit with all components has been created and the code was written in the Arduino programming language to obtain the functionality. After the software coding was completed, electronic functionality was tested, and functionality verified. The final step was the assembly of the prototype by soldering all sensors to the microcontroller board, inserting them into the 3D-printed housing and connecting the collar to the hardware.

Since the prototype had been finished it needed to be evaluated which is described in Chapter 7, the Evaluation. User tests with three different dog breeds have been conducted. During these tests dog observations by the researcher and the owner and data collection through the prototype have been conducted in real-world scenarios. A structured interview with owners after the test led to additional data collection. The test procedure is explained further in Chapter 7 itself. Additionally, the recorded data has been processed and the results and device properties analyzed, and the results discussed.

Chapter 4 – Ideation

In order to use the results of the background research to develop an initial idea and plan for the concept, this chapter describes additional research and the process of selecting the functionality and technology for the concept.

4.1 Stakeholder Identification and Analysis

Stakeholder	Interest	Influence / Power	Role
Dog	Interest in a comfortable collar that is unobtrusive and not annoying at the same time.	Low	Target user of the project. In the best case will use the product without recognizing a change. But the collar could be different in comfort which the dog would recognize.
Supervisor / Client	Successful project with a pleasing outcome and possible further developments.	High	The supervisor and Client support the project. They give feedback and a change the outcome though that.
Veterinarian	Either help to support animal welfare, because of interest in the project theme or to also profit from the outcome.	Medium / High	Support this project to help to develop a good and meaningful concept. Help with identifying the correct design and functionalities. In addition inside to medical expertise.
Dog Owners	Want to have a healthy and happy dog that has a long life. In addition, there is interest in not having large vet costs.	Medium	For the evaluation, these stakeholders will give feedback and their dogs will be wearing the collar. That results in insights and the evaluation of different aspects.

Table 2: Stakeholders, their interest and influence in this project

The supervisor and client have the highest power in this project. A weekly meeting is held in which the progress is described and feedback is given by them. The experts are needed for surveys and interviews, as the previous knowledge in the field of dog welfare and the veterinary field is limited. They have a medium to high power (depending on the scenario) and their interest is medium. The user-testing participants have low to medium power. It depends if the finalized product will be changed after the evaluation or if the evaluation leads to important insights. Their interest is not that high because they do not benefit from the project, and they won't be able to use the prototype besides the evaluation. The last stakeholder is the dog. The dog itself has a low interest and low power but is still crucial for this project.

4.2 Additional Research

The background research and the evaluation of functionalities have shown that lameness detection and heart rate measurement would be the most important functions to implement into a smart collar. Since the literature review and state of the art did not reveal any technology or information about how to implement lameness detection and the technology for heart rate measurement has not been identified, additional research is needed. Moreover, to design the first concept, gathering information about design specifications and important factors is needed as well.

4.2.1 Lameness in dogs

Another functionality that could increase the welfare of dogs, the detection of occurring lameness, has been discovered. Nalon et al. [24] define lameness as the “manifestation of a range of painful locomotory conditions affecting many species of farmed animals” [24, p. 1]. In addition, it is stated in their research that “these conditions have serious consequences for animal welfare, productivity, and longevity” [24, p. 1] regarding farm animals. When regarding dogs Harari [25] describes that lameness is a welfare problem as well and that you need to take your dog to a veterinarian in order to detect the lameness. Furthermore, lameness in animals including dogs can be treated by relieving pain, through medication or acupuncture, massages, and changes in the diet [25]. In conclusion, lameness detection could be a useful function of the smart dog collar to detect diseases, speed up treatment and relieve the dog's pain.

Rhodin et al. [26] researched a system for lameness detection in trotting dogs with induced lameness. The system contains “inertial measurement units that were attached to the head, pelvis and right distal forelimb“ [26, p. 1] of a dog. Part of the research is measuring the vertical head and pelvic movement symmetry [26]. This has been done while the dog trotted on a treadmill ”before and after induction of moderate support or swinging fore- and hindlimb lameness“ [26, p. 1]. As a next step two different variables for the head differences and two different variables for the pelvic differences were calculated [26]. The difference in these variables indicated the changes in the dog's posture and movements. The results of this study show that the system is able to detect induced moderate lameness and that it can distinguish between the lameness of the supporting and the swinging limb in dogs trotting on a treadmill [26].

4.2.2 heart rate recording technology

Electrodes

Electrodes are used for performing an electrocardiogram (ECG) which records electrical signals from the heart in order to obtain different heart related data such as the heart rate. There are electrodes that require a conducting gel that needs to be placed between the skin and the electrode before using them, which are common to use for medical human ECG recording, and dry electrodes which work without a gel.

Since the dog collar being developed as part of this research is intended for long-term daily use, the electrodes must not require shaving of the dog's hair or a conductive gel, which is why only dry electrodes are applicable to use. These dry electrodes need to be able to ensure a constant skin contact even if the dog has a dense fur. One solution to overcome this problem are dry electrodes that have extended prongs so that they can reach the skin even if there is hair or fur in between.

Figure 7: Dry Electrode with extended prongs, end of prongs touches the skin [27]

The problem with this technology is that the sensor needs to have constant skin contact and that the extended prongs could lead to skin irritation. A study that has been conducted by Marianna Koctúrová and Jozef Juhár shows the skin irritation made by a dry electrode on human skin [28].

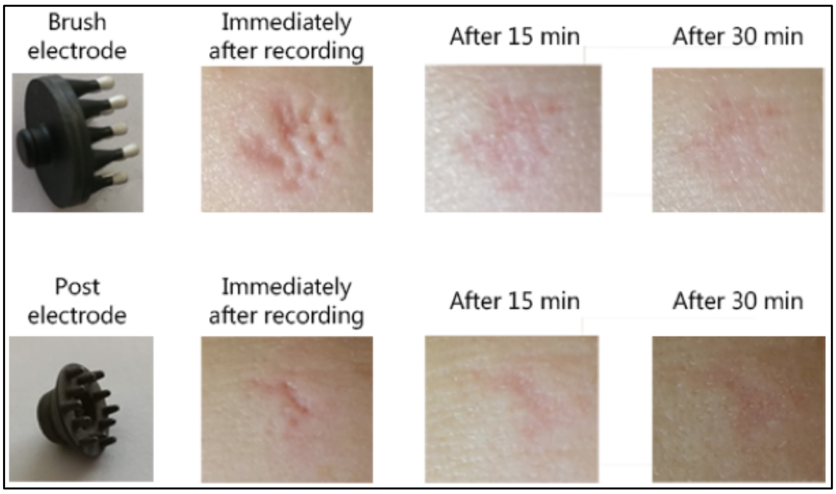

Figure 8: "Skin irritation for short term use of dry electrodes. In the top: Post electrode with pins of 2 mm length; At the bottom: Brush electrode with pins of 5 mm length" [28, p.3]

The uncertainty about the comfort and intrusiveness to the dog are the factor why this technology has not been implemented in this research, while still could be one way of measuring the heart rate and even collect more heart related data.

Radar Sensors

The only Smart Dog Collar on the market that offers the functionality of heart rate recording is developed by a company named Invoxia. "Invoxia says it worked with board-certified veterinary cardiologists to develop deep learning AI that utilizes miniaturized radar sensors — the same type as the Soli radar Google used in its Pixel 4 phones" [29, p.1]. The Google Pixel 4 Soli sensor is a partnership project between the two companies Google and Infineon Technologies AG and the sensor is based on 60GHz radar technology [30]. Infineon is selling different 60 GHz Radar sensors, however the information about these is not revealing the minimum distance for the sensor measurements. The requirement for a radar sensor in this application is that the minimum detection distance is short, preferable about under three centimeters, because it needs to gather movement data of the first layers of the dog's skin and the height of the casing needs to be low to ensure comfort to the dog. So, while the application of such a sensor is interesting because it does not require skin contact, which leads to a low amount of intrusiveness to the dog, no sensor that could be applicable has been identified and this technology is not selected for be implemented in the prototype.

Photoplethysmography (PPG)

Photoplethysmography sensors are common to use for wearable devices such as smart watches for humans. The sensor contains a light source that transmits light through the skin and a phototdector that measures the reflected light from the tissue. The reflected light can deliver data that represents the volumetric blood flow [31]. The sensor is cheap, small and has a low power consumption. One problem for using this technology on dogs is that the light and its reflection could transmit badly through the fur and could deliver non precise results. Still, a PPG sensor is selected to be used in the final prototype and the functionality is evaluated later.

4.2.3 Design and Design Specifications research

In order to design a dog collar with minimal intrusiveness and comfortable wear, not only the type of wearable but also other aspects are important. The weight of the collar is important as well so that it does not pull the dog's head down or annoy the dog while it is wearing it. As seen in Chapter 2.2 the three systems that can be attached to an existing collar have a weight between 34 and 37 grams. In addition, Valentin et al. [32] described that they found in experiments that devices that have the weight of 4% - 5% of the dog's body are still too heavy and that they strive for their “technology taking far less than 2% of the body weight.” [32, p.1280]. In addition, it is found that the technical parts or cases should be implemented in a way that they do not affect the full circumference of the collar [32]. It should leave a place at the bottom around the throat area, so the dog is able to lie down without experiencing pressure from the collar. Furthermore, Valentin et al. [32] describe the danger of strangulation through the collar and the minimum of protrusions that similar products try to achieve in order to reduce the chance of the happening of such a bad accident.

4.3 Identification of Meaningful Functionality

The background research did reveal many possible functionalities that could be implemented into a smart dog collar. In addition, further research into all types of wearables for humans has led to more functionalities. To evaluate these in terms of their meaningfulness an interview with a veterinarian with background in electrical engineering has been conducted and the list of functionalities [Appendix A.1] discusses and slightly filtered. The overview of functionalities, as a result of the interview, was processed into to a survey to evaluate them [Appendix A.2]. This survey asked the participants, which were either veterinary surgeons or researcher in the field of veterinary medicine or technology, to place each functionality into the categories: “not necessary”, “could be useful”, “important” and “very important”. The results of these surveys were analyzed and are combined in the following rating.

Rating (Top = most meaningful)	Functionality
1	Lameness detection
2	Heart Rate detection
3	Physical activity measurement (for example the step count)
3	Location detection through GPS
4	Respiration rate detection
5	Body temperature of the dog
6	Environmental temperature detection
7	Heart rate variability recording
8	Scratching and licking detection
9	Sleeping detection
10	Detection of different sleep states

Table 3: Ranking of the meaningfulness of the functionalities

4.4 Identification of the Concept's Functionalities

One important requirement for the design is the functionality of the smart dog collar. The result of the previous section needs to be discussed and a concept based on these created. The survey indicated that lameness detection in dogs is one of the most meaningful functionalities. The problem is that only one research that integrated this functionality into a prototype could be found. The research shows a prototype device that includes several IMU's that are all located on different parts of the dog's body [26]. These insights are the reason for not implementing lameness detection into the concept and prototype because of the lack of time and limited resources. On the other hand, location tracking, as being the most meaningful functionality, will be part of the functionalities that will be integrated into the collar. The results of the background research clearly show that location tracking through GPS functionality is commonly integrated into a lot of concepts and products. The next functionality, the physical activity measurement will be integrated into the concept of the device, it is meaningful, and research shows how to implement it. Another important health-related functionality is the heart rate measurement. Research shows that it is implementable by using an IMU and a gyroscope barometer or just electrodes that record the ECG. In this stage it is not clear to which extent the functionality can be achieved but it is part of the concept of the ideation phase. In addition, further research is needed to select the most suitable technology for recording heart rate in a wearable collar that fits the application of this research. Respiration rate, which is also considered to be meaningful by veterinarians, is not planned to be integrated because of the lack of reliable research on how to implement it. Measuring the body temperature of the dog is not part of the concept as well since it's difficulty of implementation. The function is usually achieved by measuring it inside of the body rectally or though the ears, which is not possible to implement into a collar that is comfortable and not intrusive to the dog. In addition, the next functionality that is considered to be part of the concept and the final prototype is environmental temperature detection, which is considered meaningful and easy to implement.

The functionalities of scratching licking and sleeping detection, the heart variability recording, and detection of different sleep states were not considered to be that important by veterinarians and they rely on many data that is hard to gather in the short time of this project.

4.5 Concept

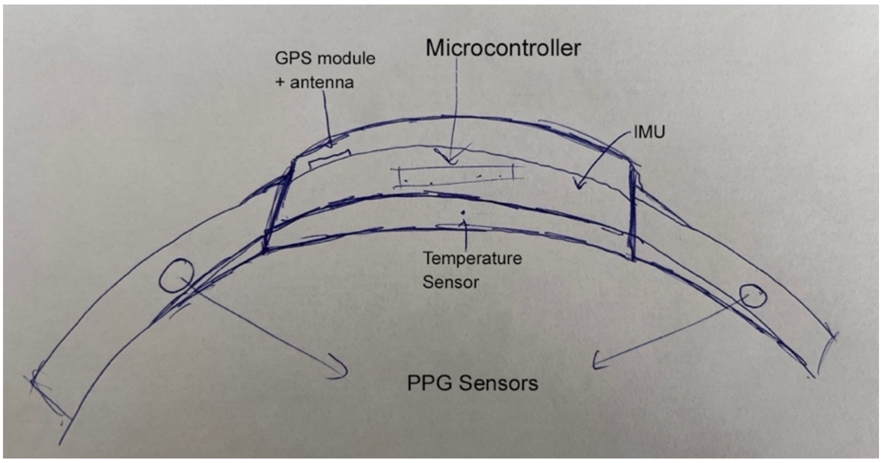

Figure 9: Concept for the Smart Dog Collar

This concept integrates a temperature sensor, Microcontroller, an IMU and PPG sensors. This hardware can lead to the following functionality:

Functionality	Technology / Hardware
Location tracking	GPS
Physical activity measurement	Inertial measurement unit (IMU)
Heart rate detection	PPG Sensor
Environmental temperature detection	Temperature sensor

Table 4: Functionalities and Technologies of the Concept

Since the concept is defined in this chapter, important additional steps before building the final prototype are to identify the functional and non-functional requirements, the design requirements and to specify the hardware used in the device.

Chapter 5 – Specification

In order to improve the idea and prepare for the realization of the prototype, it was decided to formulate functional and non-functional requirements, define specifications for the hardware and design, and conduct additional research.

5.1 Requirements

Following requirements will guide the selection of the hardware and software solutions and the Realisation phase in which the actual concept will be developed.

5.1.2 Functional Requirements

Nr.	Functional Requirement
1	The collar needs to be able to track the location with a precision at around 5 meters
2	The collar must reliably measure the ambient temperature by a precision of plus or minus 1°C
3	The collar needs to obtain data from the IMU and if possibly categorize the state of the dog into active (walking/running) or not active (resting/sleeping)
4	The system should record the raw data of the PPG sensor to be able to later process it
5	The device should store the data locally up to 12 hours
6	The battery life should exceed 12 hours
7	Integrated Sim Card and Cellular Antennas for worldwide data transfer.

Table 5: Functional Requirements for the Prototype

5.1.3 Non-Functional Requirements

Nr.	Non - Functional Requirement
1	The collar needs to be comfortable to wear with no sharp or hard elements that stick out of it that possibly can harm the dog.
2	The collar must be resistant and withstand all possible forces that could be exerted by the dog while it is moving or lying down.
3	The collar needs to be adaptive in size to make it possible to test on different dogs, ensure correct data collection and a comfortable wear.
4	The collar design needs to have minimum number of protrusions that have no holes and an even surface to minimize the risk of strangulation.
5	The collar should be durable, able to withstand various weather conditions, and be resistant to water and dust.

Table 6: Non-Functional Requirements for the Prototype

5.1.4 Requirement Prioritization

The MoSCoW method [23] is used in order to prioritize the requirements and categorize them into "Must Have", "Should Have", "Could Have" and "Will not Have". The Must-Have category contains all the requirements that are crucial to this project, part of Should-Have category are the ones which are desired to be met but not crucial and the Could-Have category contains requirements which could be integrated but are not needed for a successful research outcome. On the other side the Will-Not category includes requirements that would benefit the research or prototype but are prioritized the lowest and sorted out mainly because of the time limitation of this research. Since there are requirements which can be achieved in different levels of functionality, some of them are split up to enhance accuracy of the requirement prioritization.

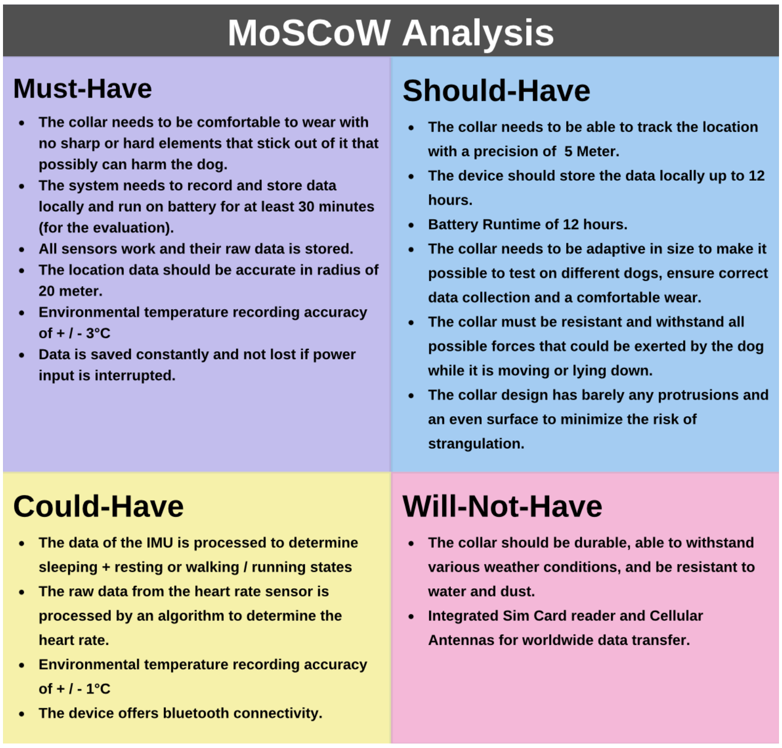

Figure 10: Results of the MoSCow Analysis, Will-Not-Have requirements are filtered out because of time limitation

5.2 Hardware Specification

It is important that the hardware components for the prototype offer a good balance between cost, battery usage, reliability, accuracy, size, and weight. Above all, the size is one of the decisive properties of the components to pack everything in a casing that is part or that can be attached to the collar. It needs to be comfortable for the dog to wear while still containing the necessary technologies and sensors. In addition to these general specifications, component specific ones are set to select the most suitable hardware for the prototype of this research.

Hardware	Specification
General	- Sensors to connect to the microcontroller board should be compatible with a Voltage of 3.3 - Dimensions under 6 cm x 3.5 cm - Compatible to Arduino (sensors) - Affordable
3D Print material	- Stiff and non-flexible - Non-toxic and safe for skin contact - Water-solid - Stereolithography (SLA) compatible
Microcontroller Board	- Compatible with Arduino - 3.3 Voltage output power pin - More than 8 digital input pins (2 for each sensor) - Bluetooth - Battery connection + charging circuit - Sufficient memory and processing capabilities - Optional features: - Temperature sensor - IMU integrated
GPS Module	- One of the smallest Arduino compatible modules - >20 Meter precision needed and 3 Meter prefered - > 40mA intake current
Temperature Sensor	- Precision +/- 1°C
PPG module	- Sensor protrudes circuit board
Battery	- Lithium Polymer - Overcharge and over-discharge protection circuitry - Lightweight and compact
SD Card reader	- Support for high-capacity SD cards
Collar	- Lightweight - Durable - Reflective elements to increase the dog’s safety

Table 7: Hardware Specifications

These additional requirements consider specific aspects of each component to ensure their functionality, compatibility, and performance align with the overall objectives of the smart dog collar. In the following these requirements are explained further.

Microcontroller board

The microcontroller should be compatible with the programming language Arduino. That requirement is set to ensure a high compatibility with many components and to simplify the data collection and processing with the use of libraries which can be easily implemented and used with Arduino. In addition, the microcontroller board needs to be small while still contain more than 8 multiple digital input pins (2 for each sensor = 8), Bluetooth for data transfer and the capability of connecting a battery. Sufficient memory and processing capabilities to handle data logging and communication tasks are important as well. Additional features such as a temperature sensor or an IMU (Inertial measurement unit) would be very beneficial to reduce the number of components but are not needed.

Location detection:

The location detection can be ensured by using the Global Position System (GPS). The usage of GPS is free and available worldwide. In order to implement this technology into the prototype a GPS Module and an antenna is needed. The requirement of a location precision of 20 meters makes it possible to locate the dog but an accuracy of 5 meters is aimed for especially making it easier to track the dog in more crowded or urban areas.

Temperature Sensor

The temperature sensor should have a precision of plus or minus 1°C and it should be usable with the Arduino with a small and light design and a low power consumption. In addition, the temperature sensor should be working between minus 30°C and plus 60°C since the usual occurring extreme temperatures are in between that range.

PPG module for Heartrate recording

For the PPG sensor it is important that the sensor, which should be as close to the skin as possible, is protruding of the circuit board. This capability can enable the housing to be designed so that the sensor is evenly aligned with the surface of the case or protrudes slightly from it.

Battery

Mainly two types of batteries can be implemented. The lithium-ion and lithium polymer battery. It was decided to choose the lithium polymer battery primarily for safety reasons. The polymer electrolyte used in lithium polymer batteries provides better resistance to thermal runaway, which is a critical issue in battery-powered devices. In addition, lithium polymer batteries have a lower risk of leakage, electrolyte evaporation, and possible fires or explosions caused by electrolyte leakage. These safety benefits, resulting from the inherent properties of the polymer electrolyte, mitigate the potential hazards associated with battery operation, providing greater safety for the user and reducing the risk of incidents. Furthermore, the battery should have an overcharge and over-discharge protection circuitry for safe and optimized battery management.

Data Storage (Memory)

The ideation concept of the previous chapter did miss the integration of an internal memory to store data. To ensure that the data can be stored on an affordably priced memory that at the same time keeps the data safe, can store a lot of data and can be easily removed from the device and connected to a computer, an SD card reader was chosen. For writing the data to a memory card, an SD card module is required. This component should small while still offering support for high-capacity SD cards. Since the maximum serial connection speed of the Arduino is only around 1 megabyte per second the speed of the component is not that important, however it is still considered during the selection.

5.3 Design Iteration and Specification

A concept for the Design was created based on the insight of the previous work. The first iteration and concept for the collar displayed below.

Figure 11: First Design Concept

After finishing the first iteration it was decided to reject this approach. Since the main part of this module would have been a big part of the device that would be 3D printed and very stiff this design approach would lead to an incompatibility with different neck circumferences of dogs. In addition, the device would not have been compatible with different collars. This understanding led to insights that resulted in the narrower specification of the design and the final idea of the design of the system. The design was changed and the plan was to put the components, with the exception of the PPG sensor, in a housing that would be as small as possible while becoming part of the collar.

Since the PPG sensors requires blood vessels under the skin at the location of the sensor, it was also determined that it should sit in an extra housing on the collar and so can be adjusted in position. This way the sensor can be placed on one of the large blood vessels in the neck for a better signal.

Chapter 6 – Realisation

In order to build the smart dog collar with the defined functionality that meets the requirements, it was decided to first select and acquire all components, then create the software and test the components, to design the system and 3D print the casing, and finally implement the components and assemble the device.

6.1 Component selection

The prior defined specifications and requirements are the basis for the selection of proper hardware to build the concept of a Smart Dog Collar. This chapter will describe and show all the components and hardware for the final prototype. To give a better understanding of the size of the components, they are shown in a picture next to a 1-euro coin for size comparison. To be mentioned is that the microcontroller does have a power output of a 3.3 Volts and all selected components are compatible with that.

6.1.1 The material for the 3D printed casing

The main case for the device will be made by using a 3D printer. The material that is selected to be used is Tough 1500 Resin from Formlabs which is "certified safe for skin contact, also making it an ideal material for wearables, personal protective equipment, and other consumer goods" [32, p. 1]. This capability ensures that the material is not toxic to the dog and is creating no skin irritations while the dog is wearing the Smart Dog Collar. Moreover, the material is water-solid and can be used with Stereolithography (SLA) 3D printer which can offers a high precision.

6.1.2 The microcontroller

To match the defined specifications the Seeedstudio Xiao Sense Ble has been selected. This device offers Bluetooth 5.0 technology, has an IMU, battery connectors, a battery charging circuit, 10 digital pins integrated and is packed into a small board with the dimensions of 20mm x 17.5mm [34]. The 32-bit ARM® Cortex™-M4 CPU which runs at 64 MHz is more than powerful enough to read and copy the sensor data and to ensure a reliable data processing. In addition, it offers a USB-C port, so the device can be connected and charged through it. This makes it easy to design the cutout for the port since it is symmetrical and increases compatibility with common charging options and cables as many other devices are already equipped with this type of port.

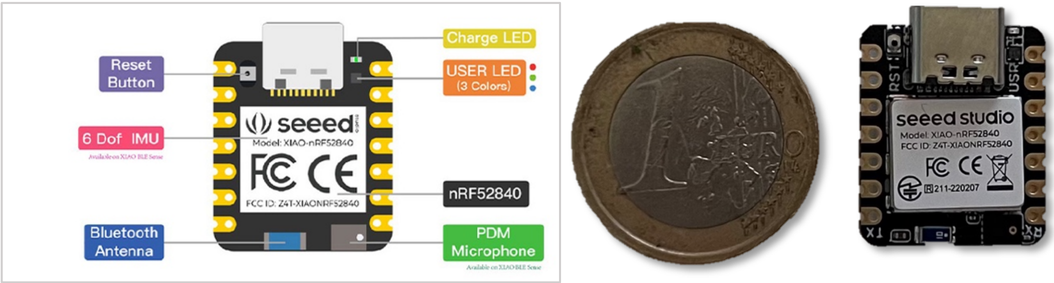

Figure 12 & 13: Overview of Seedstudio Xiao Sense Ble, size comparison [34].

6.1.3 GPS Module

The chosen GPS module is the ATGM336H, specifically selected for being the most compact and cost-effective option that is compatible with Arduino. In comparison to the most famous GPS module for Arduino, the NEO-6M which has dimensions of 23mm x 17mm, the ATGM336H is almost half the size. Its dimensions with 9.7mm x 10.1mm fulfill the requirements with having a precision of 2.5 meter in over 50% of the measurements (CEP50) and a low power consumption of under 25mA.

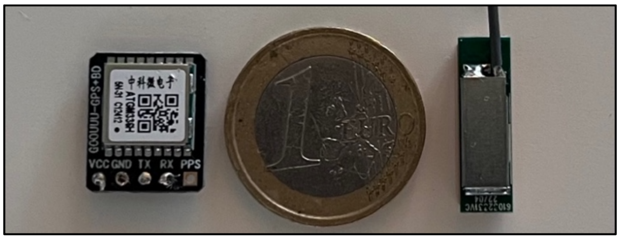

Figure 14: ATGM336H GPS Module + Antenna, size comparison 1€ Coin

6.1.4 Temperature Sensor

The temperature that is selected is the GY-68 BMP180. It offers a precision of 0.1°C, can measure temperatures between minus 40°C and plus 85°C and has the dimension of 13mm x 10mm x 2,6 mm. In addition, it has a low price and the round cutout simplifies the mounting of the sensor inside of the casing.

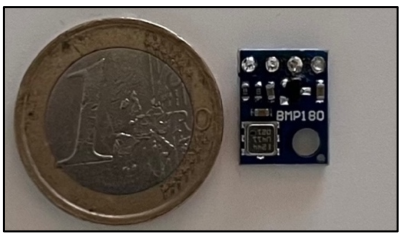

Figure 15: GY-68 BMP180 temperature sensor, size comparison 1€ coin

6.1.5 PPG-Sensor

The MAX30102 Heart Rate Sensor has been selected for the implementation into the prototype. This overall design has the advantage that the sensor, which should be as close to the dog's skin as possible, has the biggest protrusion of all PPG alternatives for the Arduino that have been found. Furthermore, the circuit and components of the PCB are located on the other side of the device so that the surface on the side of the sensor is flat. In terms of the design this protrusion simplifies the integration into a housing so that the sensors stick out of it or aligns evenly with the surface.

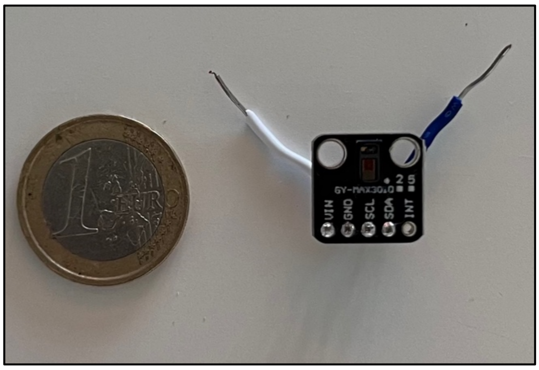

Figure 16: MAX30102, size comparison

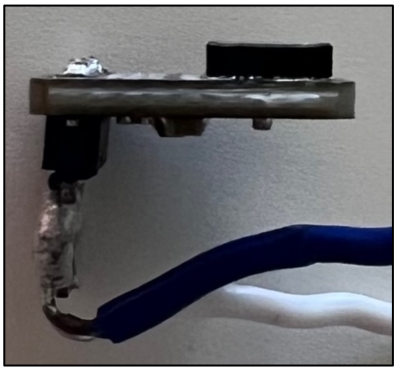

Figure 17: Protrusion of the Sensor (black component)

Other sensors that are compatible with Arduino either have a non-protruding sensor (Figure 19), there are other extrusions on the sensor side (Figure 18), or these sensors are bigger. In the following alternative, Arduino compatible sensor that have one of these flaws are shown.

Figure 18: PPG Sensor, extruding elements on PCB [35, p. 1]

Figure 19: PPG sensor, no protrusion [36, p.1]

6.1.6 Battery

The selected Lithium-Polymer battery, the EEMB LP4025356, has a Voltage of 3.7V which is the recommendation from Seeedstudio for the Xiao Sense BLE and a capacity of 320mAh. The batterie's weights only six grams and its physical dimensions are 25.5mm x 36mm x 4.3 mm. In addition to that the battery offers an overcharge, over discharge, over current, short circuit and over temperature protection which makes it safe to be part of wearable device for living things.

Figure 20: Lithium-Polymer Battery size comparison 1€ Coin

6.1.7 SD Card reader

The reader that has been chosen is from the company Youmile and only has dimensions of 17,9mm x 17,9 mm. It was the smallest SD Card reader compatible with Arduino and it is compatible with high-capacity SD Cards.

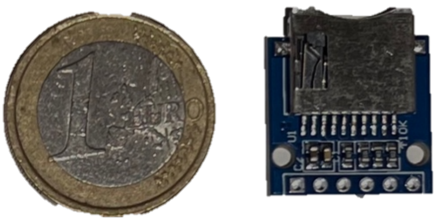

Figure 21: Youmile SD Card Reader

6.1.8 Collar

The collar that has been selected is adaptable in its size and has reflective elements. It is suitable for a neck circumference from 30 to 50 cm. Since the 3D printed case will be attached to the collar, which adds extra length, the size should match the requirements for the prototype.

6.2 Software and Circuit

This chapter described how the components have been connected, what libraires and protocols they require and the data is stored and transferred.

6.2.1 Circuit of the System

All the sensors need to be connected to the 3.3V and the ground of the microcontroller board Seeedstudio Xiao Sense BLE. The sensors use different communication and data transfer protocols. Following communication protocols are used by the components:

- UART (PIN 6, 7): ATGM336H GPS Module
- I2C (PIN 4,5): GY-68 BMP180 Temp. Sensor, MAX30102 Heart Rate Sensor
- SPI (PIN 8, 9, 10): SD-Card reader

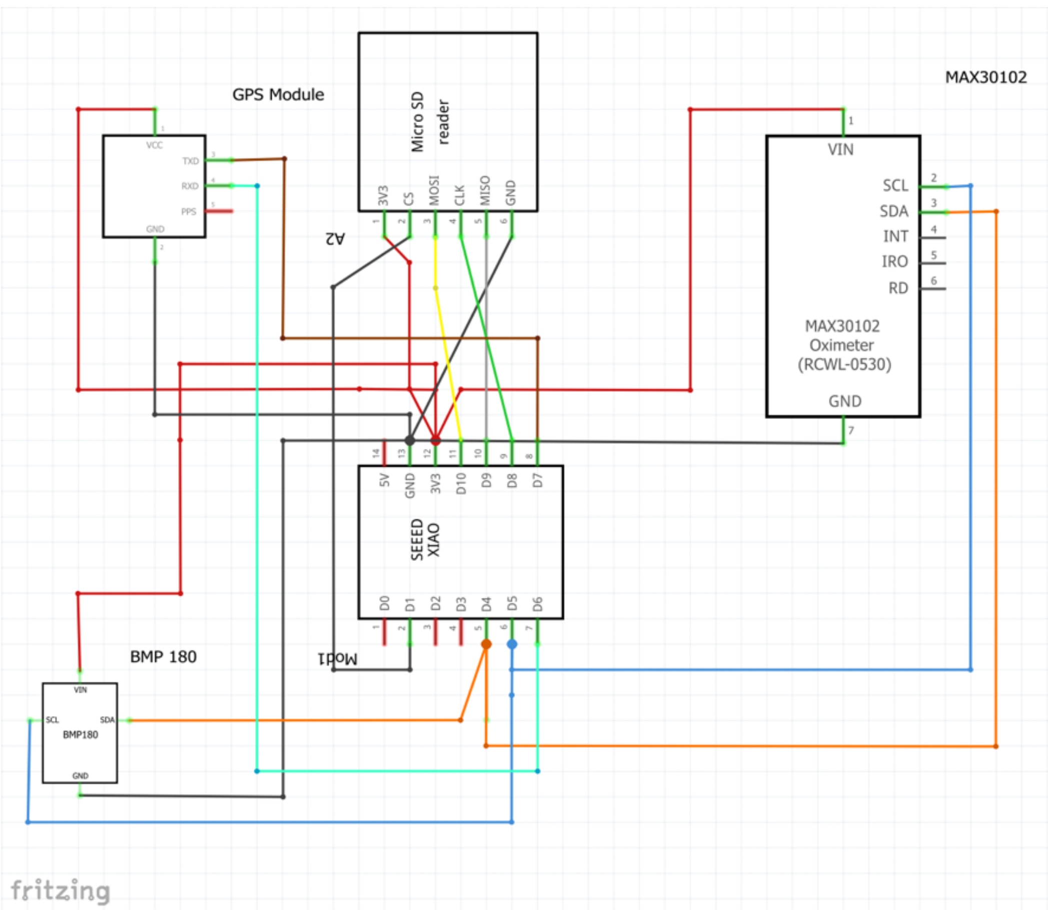

Figure 22: Circuit Diagram of the Electronical Components of the smart dog collar

6.2.2 Software

After the virtual circuit diagram have been finished all components were connected through the use of an Arduino UNO and a breadboard. After the Arduino code for every of the components had been finished, everything was merged into one program to finalize the coding. That made sure that before assembling the device and soldering all components to the Microcontroller the functionality is given.

Following Arduino Libraries are implemented into the program:

- **SparkFun MAX3010x Pulse and Proximity Sensor MAX30105:**
  Ensures the activation of the PPG sensor and the correct data readout
- **heartRate:**
  Including the algorithm for measuring the heart rate
- **Adafruit BMP085:**
  reads data from the temperature sensor
- **TinyGPSPlus:**
  parses the NMEA data streams provided by the GPS module
- **Seeed Arduino LSM6DS3:**
  Read out the data of the IMU of the Microcontroller
- **Adafruit SPIFlash**
  Activates the SPI data transfer, which is needed by the SD-Card reader
- **SdFat – Adafruit Fork:**
  Library for initializing the SD card and data transfer to it
- **ArduinoBLE:**
  Library for the Bluetooth connectivity.

6.2.3 Data storage

For an easy data readout and processing it has been decided to write the data as a csv file to the SD card. In addition, the data is extended with every 5th run of the code, which means that it is saved multiple times a second and it does not get lost when the battery is empty or any error occur. This output file contains data that can be exported as a table. Below such a table with example data is displayed.

Date	Time	GyroX	GyroY	GyroZ	AccX	AccY	AccZ	Temperature (*C)	Air Pressure (Pa)	IRvalue	HR	averageHR	GPSLat	GPSLong
27 / 6 / 2023	11:00:46.99	127.2600	-150.5700	-40.0400	0.1342	-0.8633	-0.9179	27.80	101114	40081	0.00	0	52.225351	7.362739
27 / 6 / 2023	11:00:46.99	28.7700	74.3400	10.7100	0.3611	-1.0121	-0.4768	27.80	101125	53744	0.00	0	52.225351	7.362739
27 / 6 / 2023	11:00:47.98	76.3000	266.4900	93.6600	-0.0903	-1.3191	-0.4778	27.80	101108	47515	0.00	0	52.225362	7.362746
27 / 6 / 2023	11:00:47.98	-60.6900	-29.5400	-68.3900	-0.6349	-0.9916	-0.3348	27.80	101112	68332	0.00	0	52.225362	7.362746

Figure 23: Example of Data output

6.2.4 Bluetooth Connectivity

The Bluetooth functionality enables the transfer of data of every component wirelessly to either an Android or an IOS smartphone. On Android the Application "nRF Connect for Mobile" and on IOS "LightBlue" is needed. The smartphone can be connected to the collar which gives the possibility of connecting to different services. These services represent the data transfer of one sensor so multiple on are needed. The services are shown below.

```
BLEService tempService("181A");
BLEService HeartRateAverageService("180D");
BLEService HeartRateService("1101");
BLEService GpsServiceLong("1135");
BLEService GpsServiceLat("1135");
BLEService GyroscopeService("1101");
BLEService AccelerometerService("1101");


BLEUnsignedCharCharacteristic temperatureChar("2A6E", BLERead | BLENotify);
BLEUnsignedCharCharacteristic HeartRateChar("2A37", BLERead | BLENotify);
BLEUnsignedCharCharacteristic HeartRateAVGChar("2A37", BLERead | BLENotify);
BLEFloatCharacteristic longitudeChar("2806", BLERead | BLENotify);
BLEFloatCharacteristic latitudeChar("2806", BLERead | BLENotify);
BLEFloatCharacteristic GyroscopeChar("2763", BLERead | BLENotify);
BLEFloatCharacteristic AccelChar("2763", BLERead | BLENotify);
```

Figure 24: Bluetooth Services, Arduino Code

If the device gets connected and a service selected, updated data of the corresponding sensor data will be constantly transmitted and is visible on the smartphone.

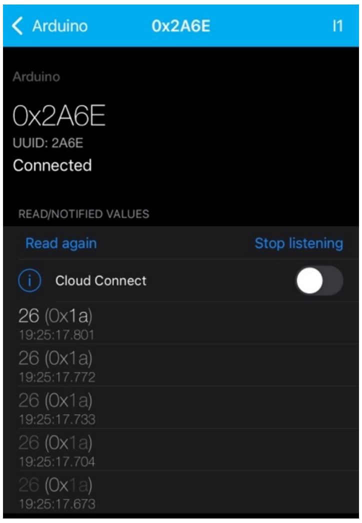

Figure 25: App Interface, Light Blue App

Above the receiving of the temperature data of 26°C is shown. Furthermore, is also possible to connect simultaneously to read out multiple sensor data at one time and receive a notification if these are changing. Figure 25 shows an example of IOS notification which reveal the temperature of 26°C and the heart rate of 72 beats per minute. One limitation is that you cannot freely name the services. Each service has an UUID and some of them are predefined for certain datatypes. The heart rate measurement for example has the UUID “2A37” which enables the displaying of “Heart Rate Measurement” inside of the app and in notifications. However no matching UUID for the other functionalities have been found so they are only displayed with their 4-digit UUID instead of a name.

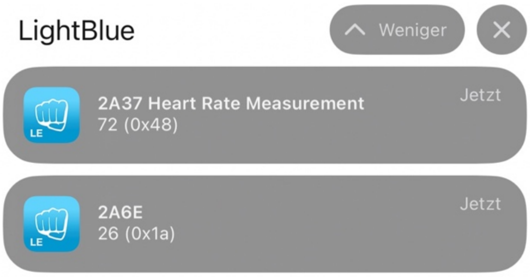

Figure 26: Notification Heart Rate and Temperature Change

6.3 Design

After the components have arrived and the circuit did work the 3D Design needed to be finalized. Since all components and hardware already had been selected the dimensions of the hardware case could be estimated much easier.

6.3.1 Design of the Main Case

Obtaining 3D Files: The first step involved acquiring the 3D files for each component, including the microcontroller board, temperature sensor, button, and the external heart rate PPG sensor module. These files were important into the program so that the case could be built around them. Furthermore, the components were tried to already position in a way that they are close together but still leave enough place for other components and the cables.

3D Modeling: After the components have been arranged in position a basic cube shape that fitted all of them was being constructed. Later the edges of the cube were smoothed, and a slight curvature was added to increase the comfort on the dog’s neck. The collar was divided into two pieces that can connect with each other to make it possible to assemble it and cutouts for the components, the UCS-B C plug and for the PPG sensor connection had been addended. To protect the components from shaking fixed positions and hooks for them were created. These hold the components in position.

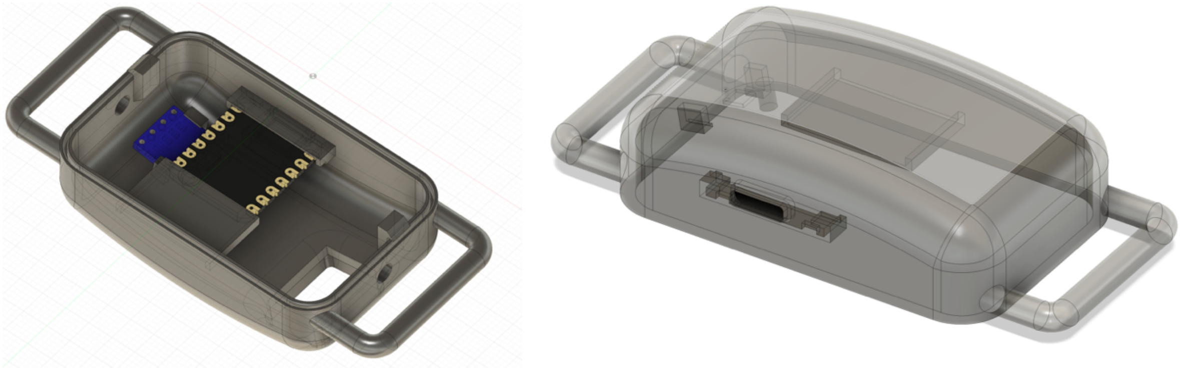

Figure 27 & 28: Fixed position of Microcontroller Board and Temperature sensor

Besides the hooks for holding the components, the temperature sensor which should measure only the environment temperature, required another specific design requirement. On the sensor itself is a small hole that directs the air into the device and measures the temperature. To lead the ambient air directly into this opening, the housing was designed with a hole.

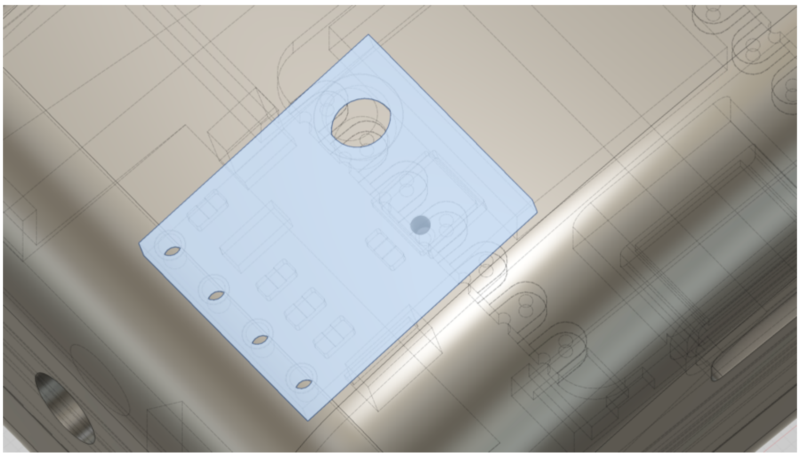

Figure 29: Air Intake Hole for Temperature Sensor

This design makes it possible so that the temperature sensor is nearly sealed to the case and that it receives mostly the environmental air to measure the temperature. In addition, the power button did also need a precise cutout to stay in place. Below is the final Design of the collar with a cutout for USB-C, connection to the Heart Rate Module and the power button. On both sides are the connection hooks on which all kind of different collars can be attached to. In addition, the underside has a thin elevation at the connection point that fits perfectly with a slot in the upper part and thus ensures a stable connection of the two parts.

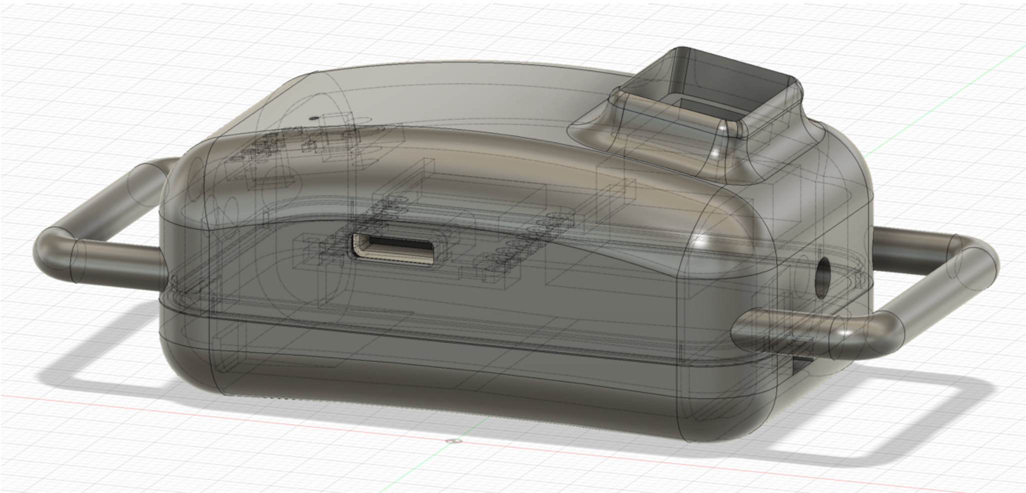

Figure 30: Final Design of the Main Module

6.3.2 Design of the Heart Rate Sensor Casing

The housing to accommodate the PPG sensor is designed to fully enclose the collar with having a strong closure and bring the sensor as close to the skin of the dog as possible. In addition, the size is kept small with dimensions of only 3.5cm x 2.5cm x 1cm to not annoy the dog.

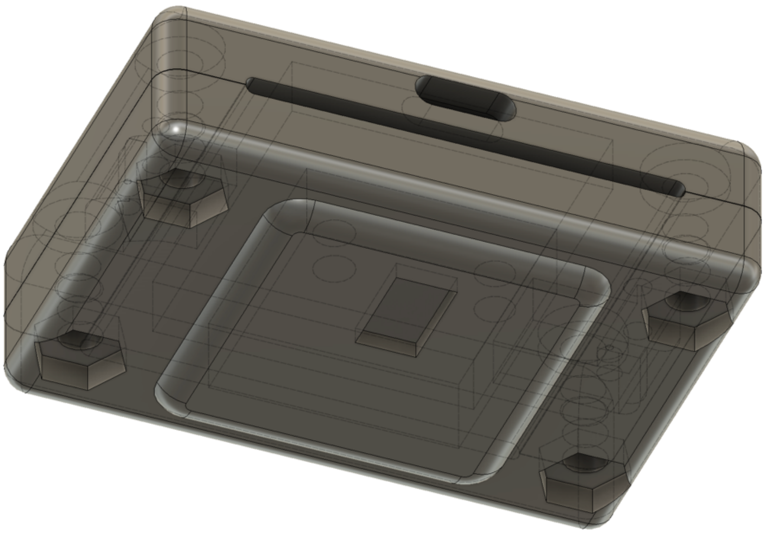

Figure 31: Final Design PPG Sensor Casing

This design meets all these requirements. It is held securely by screws, the ppg sensor is flush with the protruding surface of the module and it is very small and fits well and securely. The collar is inserted into the gap in the middle and the cables are passed through the upper pill-shaped opening.

6.4 Assembly Process

The assembly of the smart dog collar followed a systematic process that ensured integration of hardware components and especially efficient cable management. Once the 3D models and necessary software preparations were completed, 3D printing of the main housing began. After successful 3D printing, the hardware components were integrated into the casing. Each component, including the microcontroller board, sensors and external modules, were carefully positioned to maximize functionality and space utilization. To enable efficient cable management, cable lengths were estimated in advance. This allowed for precise measurements and cutting of cables, reducing cable tangles and minimizing the risk of interference. After all the cable have been cut, all necessary connections were soldered to make secure and permanent connections. Special attention was paid to soldering the nine cables to the microcontroller with a high accuracy to reduce the danger of a short circuit. After all components were connected and their functionality was checked, the battery has been connected to prevent a short circuit during the assembly. To complete the assembly, the collar was securely attached to the main housing by sewing the ends around the hooks of the main module.

Figure 32: Final Smart Dog Collar

After finalized the prototype the performance and functionality of the assembled collar needed to be examined in real-world scenarios, with a focus on improving the dog's welfare and enhancing usability. The next chapter presents the results of this evaluation.

Chapter 7 – Evaluation

The finalized prototype needs to be evaluated in terms of the design, functionality, accuracy and durability. The purpose of the evaluation is to assess the performance, usability and effectiveness of the smart dog collar. The evaluation aims to gather feedback, analyze the results, and draw conclusions about the collar's design, hardware features, accuracy, and compliance with requirements. The evaluation helps identify strengths, weaknesses, and areas for improvement to guide future iterations or improvements to the collar.

7.1 User test procedure

In order to evaluate the prototype, certain user tests were carried out. To assess the functionality and design, the prototype has been tested on different breeds of dogs. This allows to test the compatibility to different dogs and breeds and the reliability of the PPG heart rate sensor on different types of fur. The tests took place in environments that the dog already knew like the owner's home or usual areas in which the owner takes the dogs out for a walk. In total three different user tests have been conducted. In the first one especially the comfort, intrusiveness and the durability were looked at whereas in the second the accuracy of the location tracking and in the third one the accuracy of temperature senor was evaluated.

Test for the design and observation of dog's behaviour

Prior to the tests, participants (dog owners) were given a detailed briefing about the purpose of the evaluation and the specific tasks they would be asked to perform. Participants were provided with instructions on how to properly fit the smart dog collar on their dogs, ensuring a secure and comfortable fit. In addition, the owner was told to constantly observe the dog during the entire test period and to look out for signs such as unusual behaviour, discomfort of or fearful behaviour. It was made clear to the owner that if he wishes to cancel the test, he can do so at any time by telling the conductor, and that he can also remove the collar from the dog himself at any time. After the owner have applied the collar to the dog two different tests have been conducted. First, data have been recorded while the dog was lying down for 5 minutes without a lot of movement, and in the second tests the dog was taken for a walk for over 5 minutes. During these walks different scenarios such as walking, running, and playing have been performed if it was possible to do so. In addition, a walk for over 20 minutes has been conducted with two of the three participants for further data collection and observations of the dogs. During the user tests, data from the collar's hardware components, including

GPS, IMU, the PPG sensor, and the temperature sensor were collected.

After the two tests were completed, the following questions were asked:
Q1: Could you notice a difference in the dog's behaviour compared to his usual one?
Q2: Do you think your dog has shown a sign of discomfort?
Q3: Did your dog seem to be anxious?
Q4: Do you think that the collar was uncomfortable or intrusiveness to the dog.
Q5: Do you have any other feedback for the dog collar?

Test for GPS accuracy

In addition, two of the dogs (Nr.1 + Nr.2) were selected to conduct additional tests to evaluate the accuracy of the location tracking. In order to test it, the smartphone Oneplus 8 with the app GPS Logger by BasicAirData has been used for a simultaneous location recording. The recording of the collar and the smartphone has started at the same and it was tried to be as close to the dog, that wear the collar, as possible.

Test for Temperature recording accuracy

To evaluate the accuracy of the temperature sensor two simultaneously recordings have been taken to compare the data afterwards.

Selection of Comparison Device: A digital thermo-hygrometer from TFA-Dostmann, capable of measuring temperatures between -10°C and +50°C with an accuracy of 1°C, was chosen as the comparison device.

Test Setup: The Smart Dog Collar with the integrated temperature sensor was worn by the dog during the evaluation and the digital thermo-hygrometer was placed near to the collar to measure the ambient temperature. Whenever the temperature of the Thermo-Hygrometer was detected, a photo capturing display of the device with an accurate time stamp was taken.

Data comparison and analysis: The recorded temperature data of both the smart dog collar and the thermo-hygrometer were compiled into a table for comparison. The temperature graphs of the smart dog collar and the Thermo-Hygrometer were plotted to visualize the temperature readings over time and then compared with each other.

Test Subjects

Dog Nr. 1


Figure 33: Participant Dog Snoopy

Name: Snoopy

Gender: Female

Age: 9

Breed: Australian Sheppard

Neck Circumference: 44cm

Weight: 23.6 Kg

Known Health Issues: None

Dog Nr. 2


Figure 34: Participant Dog Sanji

Name: Sanji

Gender: Male

Age: 2

Breed: Italian Greyhound

Neck Circumference: 21cm

Weight: 5.25 Kg

Known Health Issues: None

Dog Nr. 3


Figure 35: Participant Dog Wölkchen

Name: Wölkchen

Gender: Female

Age: 9

Breed: Rabbit Dachshund

Neck circumference: 31cm

Weight: 4.9 Kg

Known Health Issues: None

7.2 Evaluation Results

7.2.1 Design

Results of Participant Interviews:

Participant interviews were conducted to obtain feedback on the design of the smart dog collar. The summary results of the interviews are described in the following.

Behaviour and Comfort: Participants reported that their dogs did not show any noticeable behavioural changes when wearing the smart dog collar compared to a regular collar. The dogs showed no signs of discomfort or uneasiness while wearing the collar.

Comfort and Intrusiveness: None of the participants expressed concerns about the comfort or intrusiveness of the collar. Owners felt that the collar was well tolerated by their dogs and that it did not cause discomfort or interfere with normal activities.

Additional comments: Two out of three participants specifically mentioned that they appreciated the inclusion of reflective elements in the collar's design. The reflective elements improve the dog's visibility during nighttime walks which increases safety.

7.2.2 Hardware Evaluation:

The smart dog collar was exposed to various activities during the evaluation, including ball games, running, and walking, with a total of over 4 hours of overall worn time. It is important to note that the tests were conducted in dry weather and without precipitation. The evaluation of the collar's hardware components yielded the following results:

Durability: the prototype collar proved to be robust and durable. Throughout the test period, the collar remained intact without detaching or loosening. It proved resistant to vigorous activity and showed no signs of wear or damage. The water resistance was not tested since it was decided during the specification process to not design the system specifically with this capability.

Electronic components: All the collar's electronic components, including the sensors, battery, and microcontroller were not damaged by the user testing and functioned properly after all of the testing. In addition, no solder points or other connections broke.

Housing and collar: The 3D-printed housing and collar withstood wear and tear during testing without breaking. These components proved to be reliable and durable, indicating good overall structural stability of the prototype.

Compatibility: The circumference of the collar is adjustable in the range of 30 to 53 centimeter. The collar fitted dog Nr.1 with a neck circumference of 42cm and dog Nr.3 with a neck circumference of 31cm perfect. Only dog Nr.2 that has a circumference of 21 cm was too small for a proper and tight fit around the neck. The collar did slide down slightly but did not move around much during the walk and while the dog played with a ball where it did a few sprints and jumps. Still, especially for the heart rate module a tighter fit would have been better.

In order to assess compatibility with the most popular dog breeds, information regarding Germany has been chosen due to its high dog population within the European Union [37]. Since there is a lack of comprehensive data or statistics covering all of Europe, Germany's data is considered to be representative. The following summary presents the top ten dog breeds in Germany, based on the number of new puppies born in 2020 and 2021, along with additional details about the average neck size of each breed.

Dog Breed [38]	Average Neck Circumference range - average
German Shepperd	46-60cm – 52cm
Dachshund	30-41cm – 35.5cm
German Wirehaired Pointe	46-60cm – 53cm
Labrador Retriever	46-60cm – 53cm
Poodle	30-45cm – 37.5cm
Golden Retriever	45-53cm – 49cm
German Shorthaired Pointer	38-43cm – 40.5cm
Rottweiler	61-76cm – 68.5cm
Boxer	41-56cm – 48.5cm
Small Munsterlander	45-50cm – 47.5cm

Table 8: 10 most popular dog breeds and their neck circumferences, Germany

The table shows that the collar is compatible with the average neck circumference out of 9 of the 10 most famous dog breeds in Germany. But if the maximum circumference is considered, the collar is just with 5 out of 10 dog breeds compatible. That's results in possible medium to low a compatibility with all dog breeds. Since the collar is easily interchangeable the development of two versions, one with a size from 20cm to 45cm and the other with a size from 40cm to 70cm, is being considered for possible future iterations and future research.

Weight: All components excluding the collar weights 73 grams and the overall prototype 113 grams. No literature has been found that is discussing the weight of dog collars in detail. Therefore, it was decided to compare the prototypes weight with similar products on the market and with regular dog collars. As one example Invoxia, another smart dog collar which offers functionality to enhance the wellbeing of the dog weights 165 gams [9]. The other companies that sell full collar solutions such as PetPace do not provide Information about the weight of their device. When comparing the prototype with regular collars, it was found that there are collars on the market that weight even more. One example Dog collar as that is the "JUNGLE Dog Collar" from OneTigris that weights in its smallest size 135 grams [39]. This comparison is limited but these results still indicate that the weight of the prototype smart dog collar is not unusual in comparison to normal ones, and therefore it is evaluated as a positive outcome in terms of the design of the this limitation.

7.2.3 Conclusion of Design and Hardware evaluation

These evaluation results indicate good robustness and reliability of the smart dog collar design and hardware. The collar's design was well received by both dogs and owners, and there were no findings of discomfort or behavioural problems. The prototypes' construction, including the housing and collar, proved durable during various activities. The inclusion of reflective elements further enhanced the safety properties of the collar. Overall, regarding the limitations of testing it only for a limited amount of time, these results provide valuable insight into the design and durability of the prototype of the smart dog collar. The only negative result regarding the design is the lack of compatibility with very small dog breeds which is a flaw of the design. In general, the collar has still a high compatibility with normal sized dogs but even not with really smalls ones that have a neck circumference under 30 centimeters.

7.2.3 Evaluation of the Functionality

Evaluation of Location tracking

Figure 36: GPS, high accuracy
(Blue: Oneplus 8, Violet: Dog Collar)

Figure 37: GPS, low accuracy
(Orange: Oneplus 8, Green: Dog Collar)

Moving on to the GPS location tracking functionality, the evaluation setup involved the dog wearing the active collar while the researcher recorded the signal with an Oneplus 8. In four out of the five tests, the GPS location tracking showed excellent precision, with a maximum accuracy of the difference in the data of approximately 5 meters. However, in the first test, the signal deviated significantly, with an inconsistency rate of over 40% (Figure 37), resulting in deviations of over 10 meters. No reason for that inconsistency has been found. The results show that 4 out of 5 tests, and 60% of the first test had a measurement difference under the range of a 5 meters. This leads to an accuracy of 92% (80% + 0,6 * 20%) for a 5-meter accurate location tracking to the reference device OnePlus 8 which has a high precision. This accuracy should make it possible to locate a missing dog reliably.

Evaluation of Temperature Measurement

The temperature sensing of the prototype turned out to be reliable with a maximum difference to the external thermometer of 1°C. The test was conducted for a duration of 10 minutes during a walk with the dog. The following graph shows the difference in measurements between the external thermometer and the prototype of the dog collar.

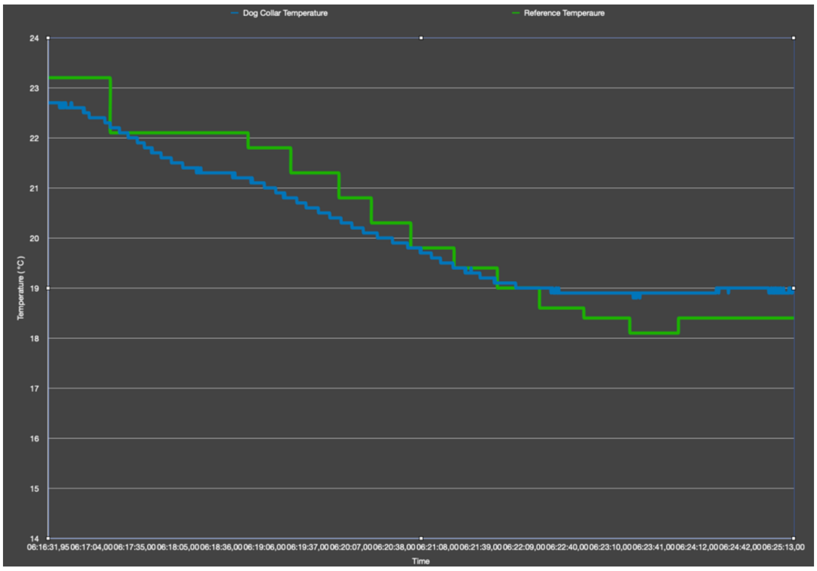

Figure 38: Temperature measurement comparison of Prototype and other Thermometer

In addition to the test, all the other datasets from previous recordings show no significant temperature gain over the time which brings the result that the inner components of the system do not heat up in a way that they influence the environmental temperature readings.

Evaluation of the IMU (Inertial Measurement Movement)

The IMU sensor that is part of the Microcontroller, the Seedstudio Xiao Sense BLE, has an accelerometer and gyroscope integrated. Both sensor data can be important for integrating a algorithm to estimating for example the step count of the. Since the algorithm is not applied and devolved in this research, only the raw data can be evaluated. To do so the accelerometer data of a test in which the dog did rest and a test in which it was walking is compared. Theoretically the data sets should be different in the differences of acceleration, where the dataset of the moving dog should have higher values.

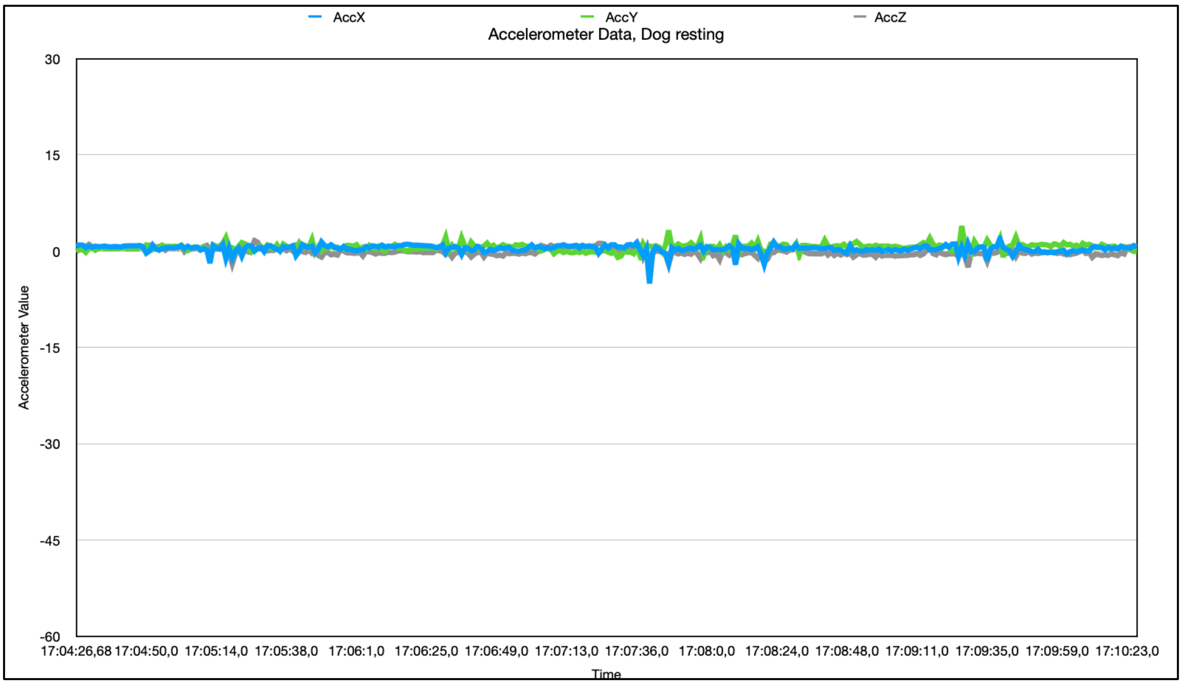

Figure 39: Graph of Accelerometer Data recording, Dog Resting

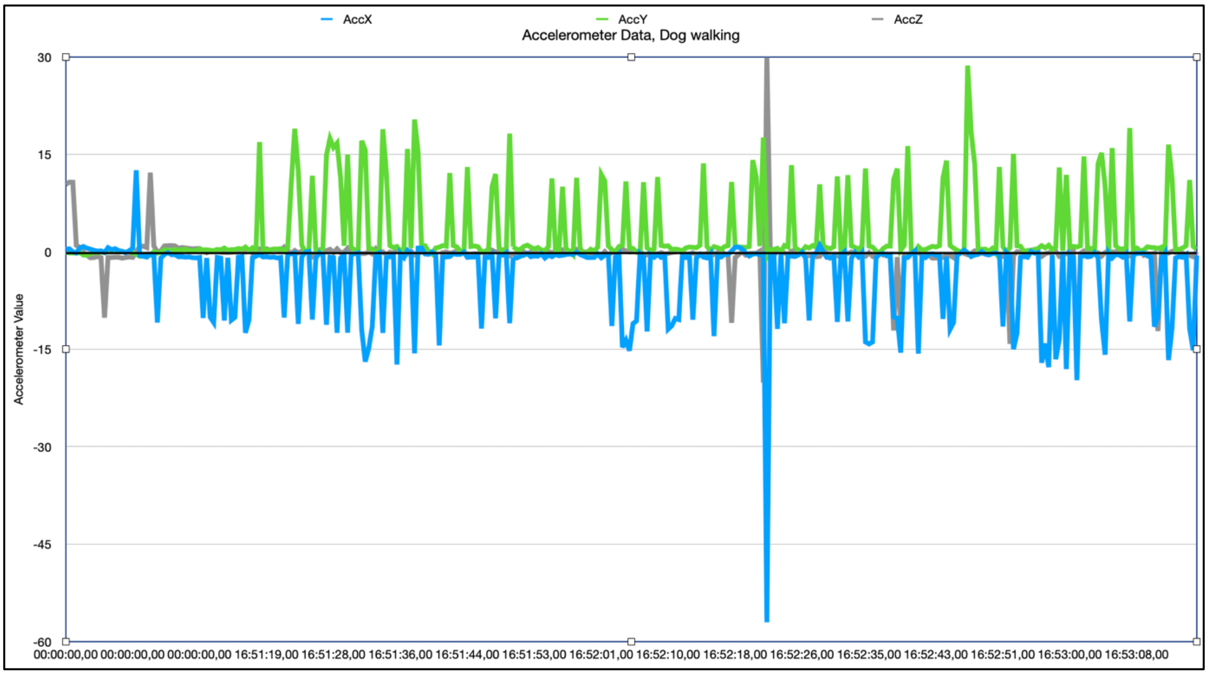

Figure 40: Graph of Accelerometer Data recording, Dog Walking

The two graphs have the same scaling on the Y-Axis which displays the Accelerometer Data. The comparison shows that there is a clear difference in the measured acceleration and that it is not a problem to tell the difference between the graphs. These results show that the development of a simple algorithm that processes the data to split parts of the wearing time of the collar in a resting / sleeping and a moving state of the dog to have a measure for the rough activity. In addition, an algorithm for counting the step of the dog should be able to integrate in the prototype like seen by modern wearable devices such as Smart Watches or Smartphones.

Evaluation of the Heart Rate Sensor

The heart rate recording functionality was tested on three dogs. The biggest challenge for the PPG sensor in this application is the fur of the dog. Dog number one and dog number three have a quite dense and long fur and dog number two has shorter one which should deliver a better result. To compare the measurement a test with a human finger has been conducted.

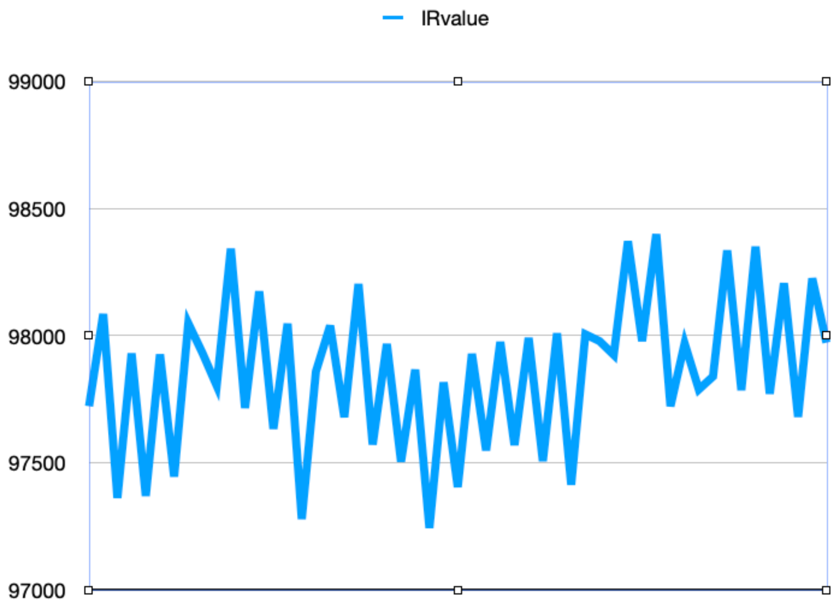

Figure 41: Graph of the raw PPG signal on human finger

The graph shows raw data of the PPG sensor on human skin. The signal shows the difference in the reflecting light depending on changes of the blood volume in blood vessels. These differences are caused by the heart rate. The high points of the curve are measured during the systolic heart action moment when the heart muscle pumps blood into the vessels, and the lower points were measured during the diastole heart action. This signal is representing a valuable and accurate measurement that can lead to the heart rate.

Measuring the PPG signal on dogs has not led to constant and reliable results in any of the tests. Different positions, dogs with different fur and tests in which the dog have been resting or walking all lead to no constant result. Figure 42 shows a result that was measured on dog number two which has the shortest fur in a setup in which the collar was fitted tight to the dog. The PPG casing have been connected to another, tighter collar that ensures proper contact to the dog.

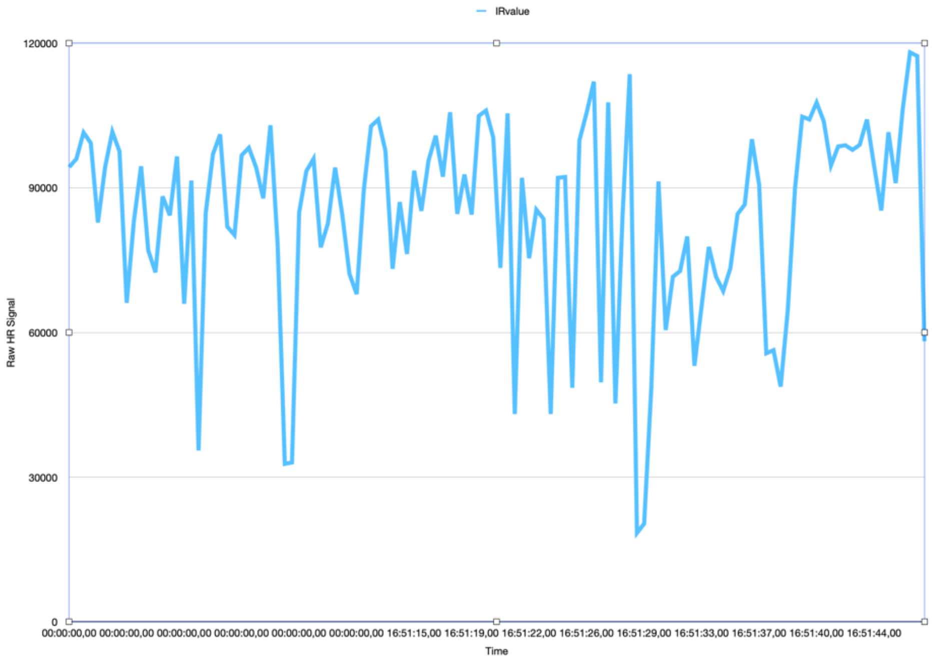

Figure 42: Raw PPG signal, prototype recording on dog's neck

If you compare the measurement from Figure 42 to the measurement on a human finger (Figure 41) or to a perfect and clean PPG signal (Figure 43) it is clear that the PPG sensor is not working reliable on the dog's neck. It is assumed that the fur does not reliably transmit the light of the PPG sensor and that therefore the recorded reflection cannot represent the blood volume changes in the microvascular bed of tissue.

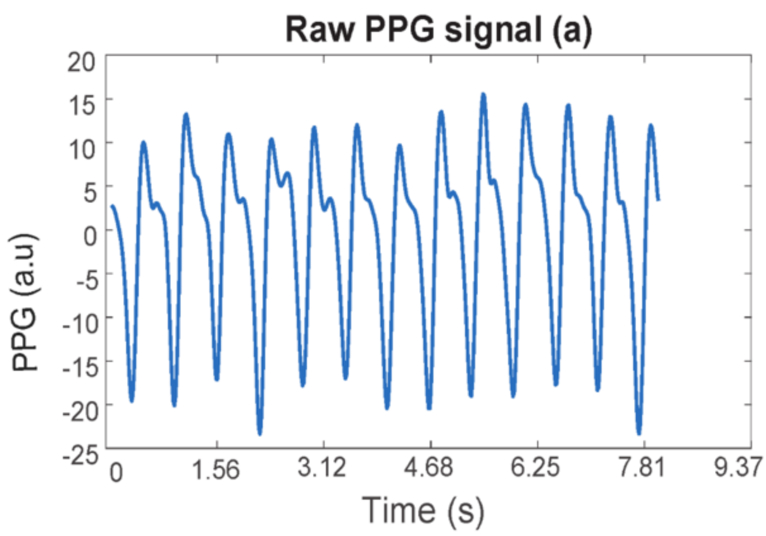

Figure 43: Example of a perfectly accurate RAW PPG signal [40]

Battery Life:

The power consumption of the device was measured through USB-C powering with an electrical pressure of ~ 5 Volts. Since the battery has a Voltage of 3.7 the consumption needs to be converted.

Figure 44: Power consumption, Bluetooth ON

Figure 45: Power Consumption, Bluetooth OFF

The energy measurements show that the device current intake is 0.034A (resistance of 154Ω) with an activated Bluetooth functionality and 0.33A (resistance of 158.9Ω) with a deactivated one. Since the voltage of the battery is lower than the measurement, the current consumption should also get lower. To calculate the change following formula, that is based on Ohm's law has been used:

$$I\ (Current) = \frac{V\ (Voltage)}{R\ (Resistance)}$$

It is considered that the resistance is not changing when powering the device with the battery. The calculations for the new Current take are as follows:

Bluetooth activated:

$$\frac{3.7V}{154\ \Omega} = 0.024\ A$$

Bluetooth deactivated:

$$\frac{3.7V}{158.9\ \Omega} = 0.0233\ A$$

To calculate the approximate battery runtime following formula has been used:

$$Batterylife\ (h) = \frac{Capacity\ (mAh)}{Consumption\ (A)}$$

Bluetooth activated:

$$\frac{320\ mAh}{24\ mA} = 13.\overline{3}\ h$$

Bluetooth deactivated:

$$\frac{320\ mAh}{23.33\ mA} = 13.72\ h$$

The pure calculation results show a battery runtime of over 13 hours for the prototype with both activated and deactivated Bluetooth. However, the results are only estimates. Actual results will depend on the condition of the battery, its age, temperature, and possibly other factors. Still if 10% of the runtime is subtracted from the results, the battery life remains about 12 hours, which fulfills the requirement of Chapter 5.

7.2.4 Results of Functionality Evaluation

All functionalities except of the heart rate measurement that have been defined before are working properly. The GPS data and temperature sensor data deliver accurate results and are fully implemented. The IMU data is not being processed through an algorithm like expected since the implementation of it has a low priority. Still the data shows promising results and a clear difference between the data recording in which the dog was resting and another one during which it was walking. Furthermore, the battery runtime exceeds 12 hours which has been defined as decent during the specification chapter so that the dog can wear the device during the day, and it can be recharged during the night. The heart rate measurement through the PPG sensor does not provide reliable data and the functionality of heart rate recording has not been achieved.

7.3 Requirement Evaluation:

The previously created requirements with their corresponding outcome are shown in the figure below. The green marks show that the requirement has been met, orange means that it has been met under certain circumstances and red means that the requirement has not been met.

Figure 46: Evaluation of Requirements, Will-Not-Have requirements are filtered out because of time limitation

Must-Have: Alle requirements have been fully met.

Should-Have: The requirement "The collar design has barely any protrusions and an even surface to minimize the risk of strangulation" has not been met in the full extend. The cable that connects the heart rate and main module has a certain length in order to adapt the placing of the heartrate module to obtain better results. During the user tests, the cable was tightly fixed to the collar by several rubber bands to prevent possible strangulation of the dog. However, this is not a permanent solution and should be solved with the help of a new design, such as integrating detachable and different length cables. All the other requirements of this category have been met.

Could-Have: The evaluation shows that the temperature sensor is working accurate with a precision of around 1°C which met the requirement. In addition, Bluetooth connectivity has been integrated into the device which enables wireless data transfer and fulfills one of the requirements. Furthermore, two requirements for the implementations of algorithms for IMU and heart rate data processing have not been implementing fully. The Heart Rate algorithm delivering constant values on the human skin but as described before it seems not to be working on the dog’s skin. The IMU Data algorithm has not been implemented in this research.

Will-Not-Have: This category contains requirements that are still useful to require but have been filtered out because of the limitation of time and the focus on the other ones.

Chapter 8 – Discussion & Future Work

8.1 Discussion

The aim of this research project was to develop a smart dog collar with minimum intrusiveness and meaningful functionality for monitoring and tracking. The results have culminated in a prototype that showcases the finalized work and the incorporated functionalities. However, it should be noted that the prototype is not a fully functional product, and certain limitations have been encountered during this research.

The inability to successfully implement heart rate recording, which was a crucial functionality of the collar, was partly due to limitations. Missing research about a valuable option for recording the heart rate, which is not intrusive or uncomfortable for the dog, was one of it. Furthermore, the doppler radar sensor emerged as a promising solution for heart rate monitoring, as it eliminates the requirement of the heart rate sensor to have skin contact. However, the unavailability of such sensors on the market, with most having a minimum detection distance of 1.5 meters or lacking detailed specifications, limited its utilization. For a collar of this nature, a minimum detection distance of a few centimeters would be necessary for practical application.

The researcher's limited educational background in veterinary medicine posed another challenge. Developing a medical tracker requires a solid understanding of veterinary knowledge. While efforts were made to compensate for this limitation through research, interviews, and consultation with veterinarians, the lack of firsthand expertise hindered the progression of certain aspects of the research.

Furthermore, the evaluation of the design was challenging due to the absence of direct involvement from veterinarians. The test was based purely on observation of the dog owner and the researcher which could give non highly accurate result. A more rigorous and standardized testing methodology involving veterinary professionals would enhance the validity of the findings but was not possible because of time limitation and the availability of veterinaries and equipment to use for the test.

Despite the encountered limitations, this research project contributes to the development of a smart dog collar with potential welfare-enhancing features. The developed design, under the recommendations, showed a device that can house different sensors, and which is lightweight and can be used of the most dog breeds. The tests indicate that the design of device is not intrusive. Moreover, the prototype demonstrates progress in terms of functionality and data collection and the research the overall meaningful functions that can be part of such a device. The successful implementation of GPS location tracking and the accurate temperature sensor showcase the feasibility of incorporating monitoring and tracking capabilities into the collar.

8.2 Future Work

In terms of future work, there are several aspects to consider for further enhancing the smart dog collar and expanding its functionalities to create a tool to enhance the canine welfare.

The implementation of a reliable heart rate recording has not been achieved in this research. To implement such a function different step can be taken. First and foremost, additional tests with PPG technology on different spots with different hardware on the dog can be conducted to see if this technology could even be working for this application. Since the application of the PPG sensor the neck of the dog is tested in this research, other spots that can be reached by a wearable could be evaluated. In addition, another approach for the future would be to explore new developments for ECG electrodes that are comfortable for dogs to wear. Alternatively, researching and implementing the use of Doppler radar sensors, which the Smart Dog Collar by Invoxia uses to measure the heart rate, could provide an alternative method. This technology would have the advantage of not requiring skin contact in difference to the PPG sensor and electrodes which simplifies data collection and increases the comfort to the dog. Another important area of development is the integration of an IMU data algorithm to detect activity tracking. This algorithm would process the data collected from the Inertial Measurement Unit (IMU) and divide the wearing time into different states such as walking and resting.

To take the prototype into a full functional product the addition of a sim card reader and antennas for cellular connection are crucial. This integration would enable real-time data transmission and remote monitoring of the dog's vital signs, activity levels, and especially the precise location if the dog has run away. Furthermore, developing a dedicated mobile application for Android and iOS platforms would allow users to conveniently access and visualize their dog's data. The application could provide comprehensive information on heart rate, temperature, GPS location, and activity levels. Users could also set alerts, track trends, and remotely interact with the collar through the app. Another aspect that could be explored is utilizing the collar's built-in microphone for behaviour detection. By implementing advanced algorithms and machine learning techniques, it may be possible to identify specific dog behaviours such as licking or scratching which can be a sign for an illness.

Moreover regarding the overall design, miniaturization, weight reduction and the addition of water-resistance should be considered to enhance the collar's practicality. This could involve designing a custom PCB (Printed Circuit Board) and transitioning the device from a prototype to a fully-fledged market-ready product. By reducing the weight and size of the collar, it would become even more comfortable for the dog to wear and water resistance could increase the resistance and reliability of the system. Another important part of the design is the circumference of the collar. During the evaluation of the device, it is found that developing two versions that differ in size should be performed. The recommendation for future research is to design one version for neck sizes from 20cm to 45cm and the other one with a size from 40cm to 70cm. If a similar design is implemented in future research where a sensor that is not part of the main casing is used, different sized cables that connect both and can be changed using plugs should be implemented. That could keep them from protruding the case and being implemented inside the collar so that there is no risk of strangulation for the dog. Additionally future research could be taken the identification of other meaningful functionalities into account.

Chapter 9 – Conclusion

The research question that leaded this research was: "How to design a smart dog collar for dogs that has minimum intrusiveness and meaningful functionality for monitoring and tracking?" This chapter presents the final conclusions based on the research findings, limitations, and results.

The design of the smart dog collar prioritized minimizing intrusiveness and discomfort for the dog. It was determined that a collar-based design is generally well-tolerated by dogs due to their familiarity with wearing such devices from an early age. The evaluation results confirm the non-intrusive and comfortable nature of the smart dog collar. Additionally, ensuring that the collar has no protrusions minimizes the risk of strangulation, prioritizing the dog's safety. The build of the hardware case, which has the technology integrated, that can be attached to a collar instead of designing a full device has the advantage of easily changing the collar, and so make it compatible to different dogs. This is especially important for prototypes of research since mostly one prototype is build which needs to be evaluated on different dogs.

The implementation of lameness detection, heart rate measurement, location tracking, physical activity measurement, respiration rate detection and body and environmental temperature detection have been identified as meaningful in terms of increasing canine welfare. This research shows how to implement location detection environmental through GPS, temperature recording, the base for activity physical activity measurement and provides an insight into the possible technologies for the heart rate recording.

The GPS technology and temperature recording used in the collar demonstrated high accuracy, providing precise location and environmental temperature tracking. Furthermore, the identified hardware components were small and lightweight, facilitating the development of a partly functional prototype.

In conclusion, this research project has laid the groundwork for the development of a smart dog collar that prioritizes the welfare of dogs through non-intrusiveness and meaningful functionality. The findings emphasize the importance of considering safety, accuracy, and comfort during the design process. By addressing the limitations through further research, collaboration, and development we can unlock the potential of this technology to significantly enhance the well-being and care of our canine companions.

References

[1] “Global pet wearable market size & share report, 2030,” Grandviewresearch.com. [Online]. Available: https://www.grandviewresearch.com/industry-analysis/pet-wearable-market. [Accessed: 27-Mar-2023].

[2] A. Zamansky, D. van der Linden, I. Hadar and S. Bleuer-Elsner, "Log My Dog: Perceived Impact of Dog Activity Tracking," in Computer, vol. 52, no. 9, pp. 35-43, Sept. 2019, doi: 10.1109/MC.2018.2889637.

[3] Alexander J. German, „The Growing Problem of Obesity in Dogs and Cats,“ in *the Journal of Nutrition*, vol. 136, 2006, pp. 1940–1946, doi: 10.1093/jn/136.7.1940S.

[4] Number of pet dogs in Europe from 2010 to 2021 (in 1,000s) [Graph], FEDIAF, September 27, 2022. [Online]. Available: https://www.statista.com/statistics/515579/dog-population-europe/. [Accessed: 05-Apr-2023].

[5] “Survey of the veterinary profession in Europe”, *Federation of Veterinarians of Europe,* 12-Oct-2019. [Online]. Available: https://fve.org/cms/wp-content/uploads/FVE_Survey_2018_WEB.pdf. [Accessed: 05-Apr-2023].

[6] D. Sec, J. Matyska, B. Klimova, R. Cimler, J. Kuhnova, and F. Studnicka, “System for detailed monitoring of dog’s vital functions,” in Computational Collective Intelligence, Cham: Springer International Publishing, 2018, pp. 426–435, doi: 10.1007/978-3-319-98443-8_39.

[7] Y. -J. Lin, C. -W. Chuang, C. -Y. Yen, S. -H. Huang and S. -Y. Lee, "Smart Pet Clothing for Monitoring of Health and Mood," 2018 IEEE International Symposium on Circuits and Systems (ISCAS), Florence, Italy, 2018, pp. 1-4, doi: 10.1109/ISCAS.2018.8351547.

[8] V. K. B. Almazan, F. I. B. Mahipus, J. R. M. Santos, and M. J. C. Samonte, “CAHM: Companion animal health monitoring system,” in Proceedings of the 2020 11th International Conference on E-Education, E-Business, E-Management, and E-Learning, 2020, doi: 10.1145/3377571.3377641.

[9] P. Khatate, A. Savkar and C. Y. Patil, "Wearable Smart Health Monitoring System for Animals," 2018 2nd International Conference on Trends in Electronics and Informatics (ICOEI), Tirunelveli, India, 2018, pp. 162-164, doi: 10.1109/ICOEI.2018.8553844.

[10] R. Brugarolas et al., "Wearable Heart Rate Sensor Systems for Wireless Canine Health Monitoring," in IEEE Sensors Journal, vol. 16, no. 10, pp. 3454-3464, May15, 2016, doi: 10.1109/JSEN.2015.2485210.

[11] A. Patil, C. Pawar, N. Patil and R. Tambe, "Smart health monitoring system for animals," 2015 International Conference on Green Computing and Internet of Things (ICGCIoT), Greater Noida, India, 2015, pp. 1560-1564, doi: 10.1109/ICGCIoT.2015.7380715.

[12] N. Hammerla, E. Hughes, P. Olivier, and T. Ploetz, “Dog's life: wearable activity recognition for dogs,” Proceedings of the 2013 ACM international joint conference on Pervasive and ubiquitous computing, pp. 415–418, 2013, doi: 10.1145/2493432.2493519.

[13] C. Zeagler et al., “Search and rescue: Dog and handler collaboration through wearable and mobile interfaces,” in Proceedings of the Third International Conference on Animal-Computer Interaction, 2016, doi: 10.1145/2995257.2995390.

[14] E. Williams, Z. Cleghern, M. Foster, T. Holder, D. Roberts and A. Bozkurt, "A Smart Collar for Assessment of Activity Levels and Environmental Conditions for Guide Dogs," 2020 42nd Annual International Conference of the IEEE Engineering in Medicine & Biology Society (EMBC), Montreal, QC, Canada, 2020, pp. 4628-4631, doi: 10.1109/EMBC44109.2020.9175814.

[15] Juneyoung Ahn, Jini Kwon, Hyejeong Nam, Hyun-Kook Jang and Jee-In Kim, "Pet buddy: A wearable device for canine behavior recognition using a single IMU," 2016 International Conference on Big Data and Smart Computing (BigComp), Hong Kong, China, 2016, pp. 419-422, doi: 10.1109/BIGCOMP.2016.7425961.

[16] “GPS tracker for dogs,” *Tractive*. [Online]. Available: https://tractive.com/en/pd/gps-tracker-dog?edition=white. [Accessed: 13-Apr-2023].

[17] “INTRODUCING SERIES 3 The smartest dog collar just got smarter.,” *Fi Smart Dog Collar*. [Online]. Available: https://tryfi.com/. [Accessed: 13-Apr-2023].

[18] “Whistle™ Health & GPS,” *Whistle*. [Online]. Available: https://www.whistle.com/products/whistle-health-gps-dog-tracker-activity-monitor. [Accessed: 13-Apr-2023].

[19] “Proactive health. Pro-level safety.,” *Smart Dog Collar - Invoxia*. [Online]. Available: https://smartdogcollar.com/en-US#techSpecFeatures. [Accessed: 13-Apr-2023].

[20] “The new PetPace Health 2.0,” *PetPace*. [Online]. Available: https://petpace.com/product/the-new-petpace-health-2-0/. [Accessed: 6-Jul-2023].

[21] “Temperature,” *PetPace*. [Online]. Available: https://petpace.com/temperature/. [Accessed: 14-Apr-2023].

[22] Mader A.H. and Eggink W., “A Design Process For Creative Technology”, Proceedings of the 16th International Conference on Engineering and product design education, Enschede, The Netherlands, 2014, pp. 568-573

[23]“What is the MoSCoW Method?,” *Software Quality.* https://www.techtarget.com/searchsoftwarequality/definition/MoSCoW-method#:~:text=The%20%20MoSCoW%20method%20is%20a [accessed Jul. 21, 2023].

[24] E. Nalon and P. Stevenson, “Addressing Lameness in Farmed Animals: An Urgent Need to Achieve Compliance with EU Animal Welfare Law,” *Animals*, vol. 9, no. 8, p. 576, Aug. 2019, doi: 10.3390/ani9080576.

[25] J. Harari, “Lameness in Dogs,” *MSD Veterinary Manual*, Oct-2022. [Online]. Available: https://www.msdvetmanual.com/dog-owners/bone,-joint,-and-muscle-disorders-of-dogs/lameness-in-dogs. [Accessed: 19-Apr-2023].

[26] M. Rhodin, A. Bergh, P. Gustås, and C. B. Gómez Álvarez, “Inertial sensor-based system for lameness detection in trotting dogs with induced lameness”, *The Veterinary Journal*, vol. 222, pp. 54–59, 2017, doi: 10.1016/j.tvjl.2017.02.004.

[27] “New Longer 5mm Spike disposable/reusable dry EEG Electrode TDE 210,” *Florida Research Instruments, Inc.* https://fri-fl-shop.com/products/new-longer-5mm-spike-disposable-reusable-dry-eeg-electrode-tde-210 [accessed Jun. 20, 2023].

[28] M. Koctúrová and J. Juhár, ‘Comparison of Dry Electrodes for Mobile EEG System’, in Conference on Theory and Practice of Information Technologies, 2019.

[29] V. Song, “This smart collar wants to be an Apple Watch for your dog,” The Verge, https://www.theverge.com/2022/1/3/22857166/invoxia-pet-tracker-smart-collar-heart-rate-dogs [accessed Jun. 23, 2023].

[30] Infineon Technologies AG, “Infineon’s innovative XENSIV™ 60 GHz radar chip enables things to see and revolutionizes the Human Machine Interface,“ *Infineon* . Available at: https://www.infineon.com/cms/en/product/promopages/60GHz/ [Accessed: 23 June 2023].

[31] D. Castaneda, A. Esparza, M. Ghamari, C. Soltanpur, and H. Nazeran, ‘A review on wearable photoplethysmography sensors and their potential future applications in health care’, *Int J Biosens Bioelectron*, vol. 4, no. 4, pp. 195–202, Aug. 2018, doi: 10.15406/ijbsbe.2018.04.00125.

[32] G. Valentin, J. Alcaidinho, and M. M. Jackson, “The Challenges of Wearable Computing for Working Dogs”, in *Adjunct Proceedings of the 2015 ACM International Joint Conference on Pervasive and Ubiquitous Computing and Proceedings of the 2015 ACM International Symposium on Wearable Computers*, Osaka, Japan, 2015, pp. 1279–1284, doi: 10.1145/2800835.2807925.

[33] “Tough 1500 resin,” *Formlabs*. [Online]. Available: https://formlabs.com/store/materials/tough-1500-resin/. [Accessed: 02-May-2023].

[34] S. Hu, “Getting started with Seeed studio Xiao NRF52840 (sense): Seeed Studio Wiki,” Seeed Studio Wiki, https://wiki.seeedstudio.com/XIAO_BLE/ [accessed Jul. 11, 2023].

[35] “MAX30102 Heart Rate and Pulse Oximeter Sensor Module (Black),” *Robotools*. https://robotools.in/shop/sensor/biometric-ecg-emg-sensor/max30102-heart-rate-and-pulse-oximeter-sensor-module-black/ [accessed June. 21, 2023].

[36] “Heart Beat Pulse Sensor Amped,” Robu.in | Indian Online Store | RC Hobby | Robotics, https://robu.in/product/pulse-sensor-amped/ [accessed Jun. 21, 2023].

[37] Number of dogs in the European Union in 2021, by country (in 1,000s) [Graph], FEDIAF, September 27, 2022. [Online]. Available: https://www.statista.com/statistics/414956/dog-population-european-union-eu-by-country/ [accessed Jul. 3, 2023].

[38] Beliebteste Hunderassen in Deutschland nach Anzahl neugeborener Welpen in den Jahren 2020 und 2021 (Top 150) [Graph], VDH, September 8, 2022. [Online]. Available: https://de.statista.com/statistik/daten/studie/29273/umfrage/hundezucht-beliebteste-hunderassen-in-deutschland/ [accessed Jul. 3, 2023].

[39] “Jungle dog collar,” Onetigris, https://www.onetigris.com/eu/jungle-dog-collar.html [accessed Jul. 1, 2023].

[40] G. Masinelli, F. Dell’Agnola, A. A. Valdés, and D. Atienza, “SPARE: A Spectral Peak Recovery Algorithm for PPG Signals Pulsewave Reconstruction in Multimodal Wearable Devices,” *Sensors*, vol. 21, no. 8, p. 2725, Apr. 2021, doi: 10.3390/s21082725.

Appendix

Appendix A – Interview and Survey:

A.1 List of functionalities discussed with a veterinarian:

- Heat measurement of dog's body temperature
- Scratching and licking detection
- Sleeping detection
- Respiration rate detection
- Heart rate recording
- Heart rate variability recording
- electrocardiogram (ECG) recording
- epileptic seizure detection
- blood pressure measurement
- physical activity measurement
- lameness detection
- behaviour detection
- environmental humidity and temperature detection
- location detection through GPS
- tracking of sleep states
- Blood oxygen level measurement

A.2 Survey Meaningful functionalities:

Veterinarian Survey for the functionalities of a Smart Dog Collar

How would you rate the following features of a smart dog collar in terms of importance and usefulness?

The following can be assessed by marking the corresponding answer in the table with "x"		Not necessary	Could be useful	important	Very important	Not sure
1	Environmental temperature					
2	Body temperature of the dog					
3	Scratching and licking detection					
4	Sleeping detection					
5	Detection of different sleep states					
6	Respiration rate detection					
7	Heart Rate detection					
8	Heart rate variability recording					
9	Physical activity measurement (for example the step count)					
10	Lameness detection					
11	Location detection through GPS					

Do you have any comments or want to discuss a functionality? (You can use the number from the table to refer to one certain functionality.)

Do you have another functionality in mind that is not part of the list?

Thank you for filling out this survey!

Appendix B – Arduino Code:

B.1 Arduino Code with Bluetooth implementation

```
#include <Wire.h>              //general Libary
#include "MAX30105.h"          //heart rate
#include "heartRate.h"         //heart rate
#include <Adafruit_BMP085.h>   //Temperature
#include <Arduino.h>           //GPS
#include <TinyGPSPlus.h>       //GPS
#include "LSM6DS3.h"           //IMU
#include <SPI.h>               //SD Card
#include <SdFat.h>             //SD Card
#include <ArduinoBLE.h>        //Bluetooth

#define FILE_BASE_NAME "CollarData"  //Base Name of SDCARD File

MAX30105 particleSensor;                                  //HeartRate
Adafruit_BMP085 bmp;                                      //Temperature
TinyGPSPlus gps;                                          //GPS
LSM6DS3 IMU(I2C_MODE, 0x6A);                              //I2C device address (0x6A) of the IMU
File myFile;                                              //For SD Card
SdFat SD;                                                 //For SD Card
BLEService ledService("19B10000-E8F2-537E-4F6C-D104768A1214");  // Bluetooth® Low Energy LED Service

//Variables for the HeartRateSensor
const byte RATE_SIZE = 5;  //Increase this for more averaging. 4 is good.
byte rates[RATE_SIZE];     //Array of heart rates
byte rateSpot = 0;
long lastBeat = 0;  //Time at which the last beat occurred
float beatsPerMinute;
int beatAvg;
long valueOfIR;

//Varibale for SD Card
const uint8_t CS_PIN = 1;  //SD Module connected PIN1
const uint8_t BASE_NAME_SIZE = sizeof(FILE_BASE_NAME) - 1;
char fileName[] = FILE_BASE_NAME "00.csv";


unsigned long previousMillis = 0;
const unsigned long interval = 1000;  // Interval between SD card writes (in milliseconds)

int placeholder = 0000;

int counter;


//Variables Bluetooth Connection
float temperature;
float gyro;
float accelerometer;
float longitudeData;
float latitudeData;


BLEService tempService("181A");              //Environmental Sesning Service
```

```
BLEService HeartRateAverageService("180D");  //Generic Health Sensor service
BLEService HeartRateService("1101");         //Heart Rate service
BLEService GpsServiceLong("1135");           //GNSS
BLEService GpsServiceLat("1135");            //GNSS
BLEService GyroscopeService("1101");         //SerialPort
BLEService AccelerometerService("1101");     //SerislPort


BLEUnsignedCharCharacteristic temperatureChar("2A6E", BLERead | BLENotify);   // standard 16-bit characteristic UUID
BLEUnsignedCharCharacteristic HeartRateChar("2A37", BLERead | BLENotify);     // standard 16-bit characteristic UUID
BLEUnsignedCharCharacteristic HeartRateAVGChar("2A37", BLERead | BLENotify);  // standard 16-bit characteristic UUID
BLEFloatCharacteristic longitudeChar("2806", BLERead | BLENotify);            // standard 16-bit characteristic UUID
BLEFloatCharacteristic latitudeChar("2806", BLERead | BLENotify);             // standard 16-bit characteristic UUID
BLEFloatCharacteristic GyroscopeChar("2763", BLERead | BLENotify);            // standard 16-bit characteristic UUID
BLEFloatCharacteristic AccelChar("2763", BLERead | BLENotify);                // standard 16-bit characteristic UUID

// Latutude: 2AAE Environment Sensing
// Longitude: 2AAF EnvironmetnSensing
// Temperature: 0x2A6E
// Heart Rate Measurement: 0x2A37
// plane angle (degree): 0x2763

void setup() {
  Serial.begin(9600);
  Serial1.begin(9600);  //TX and RX Pin (Connect module the other way around -> Rx to TX ), GPS module bps 9600

  pinMode(1, OUTPUT);  //OUTPUT Pin of SD Card

  if (!SD.begin(CS_PIN)) {
    Serial.println(F("begin failed"));
    //return;
  }

  if (!BLE.begin()) {
    Serial.println("starting Bluetooth® Low Energy module failed!");
  }

  /*-------------SD--------------*/
  while (SD.exists(fileName)) {
    if (fileName[BASE_NAME_SIZE + 1] != '9') {
      fileName[BASE_NAME_SIZE + 1]++;
    } else if (fileName[BASE_NAME_SIZE] != '9') {
      fileName[BASE_NAME_SIZE + 1] = '0';
      fileName[BASE_NAME_SIZE]++;
    } else {
      Serial.println(F("Can't create file name"));
    }
  }
  myFile = SD.open(fileName, FILE_WRITE);  //Open SD-Card

  if (!myFile) {
    Serial.println(F("open failed"));
  }
  myFile.println("Date, Time, GyroX, GyroY, GyroZ, AccX, AccY, AccZ, Temperature (*C), Air Pressure (Pa), IRvalue, HR, averageHR,
GPSLat, GPSLong");
  myFile.close();
```

```
/*-----------END SD, Start IMU------------*/
if (IMU.begin() != 0) {
  Serial.println("Device error");
} else {
  Serial.println("IMU OK!");
}

/*---------------heart rate sensor---------------*/
// Initialize HR sensor, if no sensor, print it
if (!particleSensor.begin(Wire, I2C_SPEED_FAST)) {  //Use default I2C port, 400kHz speed
  Serial.println("MAX30105 was not found.");
}

particleSensor.begin(Wire, I2C_SPEED_FAST);

particleSensor.setup();                     //Configure sensor with default settings
particleSensor.setPulseAmplitudeRed(0x0A);  //Turn Red LED to low to indicate sensor is running
particleSensor.setPulseAmplitudeGreen(0);   //Turn off Green LED
/*-----------------------*/

/*-------------temperature sensor---------------*/
//if no valid temperature sensor, print it
bmp.begin();
if (!bmp.begin()) {
  Serial.println("Could not find a valid BMP085 sensor, check wiring!");
}
counter = 101;

/*------------------Bluetooth--------------------*/
BLE.setLocalName("COLLAR");


BLE.setAdvertisedService(tempService);           // add the service UUID
tempService.addCharacteristic(temperatureChar);  // add the temperature characteristic
BLE.addService(tempService);                     // Add the temperature service
temperatureChar.writeValue(0);                   // set initial value for this characteristic (0)

BLE.setAdvertisedService(HeartRateService);
HeartRateService.addCharacteristic(HeartRateChar);
BLE.addService(HeartRateService);
HeartRateChar.writeValue(0);

BLE.setAdvertisedService(HeartRateAverageService);
HeartRateAverageService.addCharacteristic(HeartRateAVGChar);
BLE.addService(HeartRateAverageService);
HeartRateAVGChar.writeValue(0);

BLE.setAdvertisedService(GpsServiceLong);
GpsServiceLong.addCharacteristic(longitudeChar);
BLE.addService(GpsServiceLong);
longitudeChar.writeValue(0);

BLE.setAdvertisedService(GpsServiceLat);
GpsServiceLat.addCharacteristic(latitudeChar);
BLE.addService(GpsServiceLat);
latitudeChar.writeValue(0);
```

```
  BLE.setAdvertisedService(GyroscopeService);
  GyroscopeService.addCharacteristic(GyroscopeChar);
  BLE.addService(GyroscopeService);
  GyroscopeChar.writeValue(0);

  BLE.setAdvertisedService(AccelerometerService);
  AccelerometerService.addCharacteristic(AccelChar);
  BLE.addService(AccelerometerService);
  AccelChar.writeValue(0);


  BLE.advertise();  //start Bluetooth advertising
}



void loop() {
  // listen for Bluetooth® Low Energy peripherals to connect:
  BLEDevice central = BLE.central();

  counter++;
  /*----------heart rate sensor------------*/
  long irValue = particleSensor.getIR();
  valueOfIR = irValue;

  if (checkForBeat(irValue) == true) {

    Serial.println("CHECKxxFORxxBEAT");
    //We sensed a beat!
    long delta = millis() - lastBeat;
    lastBeat = millis();

    beatsPerMinute = 60 / (delta / 1000.0);

    if (beatsPerMinute < 255 && beatsPerMinute > 50) {
      rates[rateSpot++] = (byte)beatsPerMinute;  //Store this reading in the array
      rateSpot %= RATE_SIZE;                     //Wrap variable

      //Take average of readings
      beatAvg = 0;
      for (byte x = 0; x < RATE_SIZE; x++)
        beatAvg += rates[x];
      beatAvg /= RATE_SIZE;
    }
  }


  /*-------------GPS sensor--------------*/
  while (Serial1.available() > 0) {
    char c = (Serial1.read());
    gps.encode(c);
  }

  bmp.readTemperature();  //get a more continous Temperature (Fails sometimes if not called here)

  Serial.print("IR=");
  Serial.print(irValue);
```

```
  Serial.print(", BPM=");
  Serial.print(beatsPerMinute);
  Serial.print(", Avg BPM=");
  Serial.println(beatAvg);


  if (gps.location.isValid()) {
    Serial.print(gps.location.lat(), 6);
    Serial.print(", ");
    Serial.println(gps.location.lng(), 6);
  } else {
    Serial.print("INVALID ,");
    Serial.println("INVALID");
  }

  Serial.println(IMU.readFloatGyroX(), 4);
  Serial.println(IMU.readFloatGyroY(), 4);
  Serial.println(IMU.readFloatGyroZ(), 4);
  Serial.println(IMU.readFloatAccelX(), 4);
  Serial.println(IMU.readFloatAccelY(), 4);
  Serial.println(IMU.readFloatAccelZ(), 4);


  writeToSD();
  sendToBluetooth();
}

void sendToBluetooth() {

  temperature = bmp.readTemperature();
  gyro = IMU.readFloatGyroX() + placeholder + IMU.readFloatGyroY() + placeholder + IMU.readFloatGyroZ();
  accelerometer = IMU.readFloatAccelX() + placeholder + IMU.readFloatAccelY() + placeholder + IMU.readFloatAccelZ();
  longitudeData = gps.location.lng();
  latitudeData = gps.location.lat();


  temperatureChar.writeValue(temperature);
  HeartRateChar.writeValue(beatsPerMinute);
  HeartRateAVGChar.writeValue(beatAvg);
  longitudeChar.writeValue(longitudeData);
  latitudeChar.writeValue(latitudeData);
  GyroscopeChar.writeValue(gyro);
  AccelChar.writeValue(accelerometer);
}


void writeToSD() {

  if (counter > 5) {
    myFile = SD.open(fileName, FILE_WRITE);
  }

  String p1 = ", ";
  String p2 = " / ";


  // -------Date----------
  if (gps.date.isValid()) {
```

```
    myFile.print(gps.date.day() + p2 + gps.date.month() + p2 + gps.date.year() + p1);
  } else {
    myFile.print(F("INVALID ,"));
  }
  // --------Time----------
  if (gps.time.isValid()) {
    if (gps.time.hour() < 10) myFile.print(F("0"));
    myFile.print(gps.time.hour());
    myFile.print(":");
    if (gps.time.minute() < 10) myFile.print(F("0"));
    myFile.print(gps.time.minute());
    myFile.print(":");
    if (gps.time.second() < 10) myFile.print(F("0"));
    myFile.print(gps.time.second());
    myFile.print(".");
    if (gps.time.centisecond() < 10) myFile.print(F("0"));
    myFile.print(gps.time.centisecond());
    myFile.print(" ,");
  } else {
    myFile.print(F("INVALID ,"));
  }
  myFile.print(IMU.readFloatGyroX(), 4);
  myFile.print(", ");

  myFile.print(IMU.readFloatGyroY(), 4);
  myFile.print(", ");

  myFile.print(IMU.readFloatGyroZ(), 4);
  myFile.print(", ");

  myFile.print(IMU.readFloatAccelX(), 4);
  myFile.print(", ");

  myFile.print(IMU.readFloatAccelY(), 4);
  myFile.print(", ");

  myFile.print(IMU.readFloatAccelZ(), 4);
  myFile.print(", ");

  myFile.print(bmp.readTemperature() + p1 + bmp.readPressure() + p1 + valueOfIR + p1 + beatsPerMinute + p1 + beatAvg + p1);


  if (gps.location.isValid()) {
    myFile.print(gps.location.lat(), 6);
    myFile.print(",");
    myFile.println(gps.location.lng(), 6);
  } else {
    myFile.print("INVALID ,");
    myFile.println("INVALID");
  }


  if (counter > 5) {
    myFile.close();
    counter = 0;
  }
}
```

B.2 Arduino Code without Bluetooth implementation

```
#include <Wire.h>              //general Libary
#include "MAX30105.h"          //heart rate
#include "heartRate.h"         //heart rate
#include <Adafruit_BMP085.h>   //Temperature
#include <Arduino.h>           //GPS
#include <TinyGPSPlus.h>       //GPS
#include "LSM6DS3.h"           //IMU
#include <SPI.h>               //SD Card
#include <SdFat.h>             //SD Card

#define FILE_BASE_NAME "CollarData"  //Base Name of SDCARD File

MAX30105 particleSensor;       //HeartRate
Adafruit_BMP085 bmp;           //Temperature
TinyGPSPlus gps;               //GPS
LSM6DS3 IMU(I2C_MODE, 0x6A);   //I2C device address (0x6A) of the IMU
File myFile;                   //For SD Card
SdFat SD;                      //For SD Card

//Variables for the HeartRateSensor
const byte RATE_SIZE = 5;  //Increase this for more averaging. 4 is good.
byte rates[RATE_SIZE];     //Array of heart rates
byte rateSpot = 0;
long lastBeat = 0;  //Time at which the last beat occurred
float beatsPerMinute;
int beatAvg;
long irValue;
//Varibale for SD Card
const uint8_t CS_PIN = 1;  //SD Module connected PIN1
const uint8_t BASE_NAME_SIZE = sizeof(FILE_BASE_NAME) - 1;
char fileName[] = FILE_BASE_NAME "00.csv";


unsigned long previousMillis = 0;
const unsigned long interval = 1000;  // Interval between SD card writes (in milliseconds)

int counter;


void setup() {
  Serial.begin(9600);
  Serial1.begin(9600);  //TX and RX Pin (Connect module the other way around -> Rx to TX ), GPS module bps 9600

  pinMode(1, OUTPUT);  //OUTPUT Pin of SD Card

  if (!SD.begin(CS_PIN)) {
    Serial.println(F("begin failed"));
  }

  /*-------------SD-------------*/
  while (SD.exists(fileName)) {
    if (fileName[BASE_NAME_SIZE + 1] != '9') {
      fileName[BASE_NAME_SIZE + 1]++;
    } else if (fileName[BASE_NAME_SIZE] != '9') {
      fileName[BASE_NAME_SIZE + 1] = '0';
```

```
      fileName[BASE_NAME_SIZE]++;
    } else {
      Serial.println(F("Can't create file name"));
    }
  }
  myFile = SD.open(fileName, FILE_WRITE);  //Open SD-Card

  if (!myFile) {
    Serial.println(F("open failed"));
  }
  myFile.println("Date, Time, GyroX, GyroY, GyroZ, AccX, AccY, AccZ, Temperature (*C), Air Pressure (Pa), IRvalue, HR, averageHR,
GPSLat, GPSLong");
  myFile.close();

  /*-----------END SD, Start IMU------------*/
  if (IMU.begin() != 0) {
    Serial.println("Device error");
  } else {
    Serial.println("IMU OK!");
  }

  /*--------------heart rate sensor--------------*/
  if (!particleSensor.begin(Wire, I2C_SPEED_FAST)) {  //Use default I2C port, 400kHz speed
    Serial.println("MAX30105 was not found.");
  }

  particleSensor.begin(Wire, I2C_SPEED_FAST);

  particleSensor.setup();                     //Configure sensor with default settings
  particleSensor.setPulseAmplitudeRed(0x0A);  //Turn Red LED to low to indicate sensor is running
  particleSensor.setPulseAmplitudeGreen(0);   //Turn off Green LED
  /*-----------------------*/

  /*-------------temperature sensor--------------*/
  //if no valid temperature sensor, print it
  bmp.begin();
  if (!bmp.begin()) {
    Serial.println("Could not find a valid BMP085 sensor, check wiring!");
  }
  counter = 101;
  /*-------------------------------------*/
}


void loop() {

  counter++;
  /*----------heart rate sensor------------*/
  irValue = particleSensor.getIR();


  if (checkForBeat(irValue) == true) {
    //We sensed a beat!
    long delta = millis() - lastBeat;
    lastBeat = millis();
    beatsPerMinute = 60 / (delta / 1000.0);
```

```
    if (beatsPerMinute < 255 && beatsPerMinute > 50) {
      rates[rateSpot++] = (byte)beatsPerMinute;  //Store this reading in the array
      rateSpot %= RATE_SIZE;                     //Wrap variable

      //Take average of readings
      beatAvg = 0;
      for (byte x = 0; x < RATE_SIZE; x++)
        beatAvg += rates[x];
      beatAvg /= RATE_SIZE;
    }
  }

  /*-------------GPS sensor---------------*/
  while (Serial1.available() > 0) {
    char c = (Serial1.read());
    gps.encode(c);
  }

  bmp.readTemperature();  //get a more continous Temperature (Fails sometimes if not called here)
  writeToSD();
  /*--------------------------------------*/
}


void writeToSD() {

  if (counter > 5) {
    myFile = SD.open(fileName, FILE_WRITE);
  }

  String p1 = ", ";
  String p2 = " / ";


  // -------Date----------
  if (gps.date.isValid()) {
    myFile.print(gps.date.day() + p2 + gps.date.month() + p2 + gps.date.year() + p1);
  } else {
    myFile.print(F("INVALID ,"));
  }
  // --------Time----------
  if (gps.time.isValid()) {
    if (gps.time.hour() < 10) myFile.print(F("0"));
    myFile.print(gps.time.hour());
    myFile.print(":");
    if (gps.time.minute() < 10) myFile.print(F("0"));
    myFile.print(gps.time.minute());
    myFile.print(":");
    if (gps.time.second() < 10) myFile.print(F("0"));
    myFile.print(gps.time.second());
    myFile.print(".");
    if (gps.time.centisecond() < 10) myFile.print(F("0"));
    myFile.print(gps.time.centisecond());
    myFile.print(" ,");
  } else {
```

```
    myFile.print(F("INVALID ,"));
  }


  myFile.print(IMU.readFloatGyroX(), 4);
  myFile.print(", ");

  myFile.print(IMU.readFloatGyroY(), 4);
  myFile.print(", ");

  myFile.print(IMU.readFloatGyroZ(), 4);
  myFile.print(", ");

  myFile.print(IMU.readFloatAccelX(), 4);
  myFile.print(", ");

  myFile.print(IMU.readFloatAccelY(), 4);
  myFile.print(", ");

  myFile.print(IMU.readFloatAccelZ(), 4);
  myFile.print(", ");

  myFile.print(bmp.readTemperature() + p1 + bmp.readPressure() + p1 + irValue + p1 + beatsPerMinute + p1 + beatAvg + p1);



  if (gps.location.isValid()) {
    myFile.print(gps.location.lat(), 6);
    myFile.print(",");
    myFile.println(gps.location.lng(), 6);
  } else {
    myFile.print("INVALID ,");
    myFile.println("INVALID");
  }


  if (counter > 5) {
    myFile.close();
    counter = 0;
  }
}
```