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GRADO EN INGENIERÍA EN TECNOLOGÍAS INDUSTRIALES

TRABAJO FIN DE GRADO

AUTONOMOUS DOG TRAINING COLLAR

Autor: Javier Ugedo Pérez

Director: Leonard Frank Register

Madrid

Junio de 2025

Declaro, bajo mi responsabilidad, que el Proyecto presentado con el título

Autonomous Dog Training Collar

en la ETS de Ingeniería - ICAI de la Universidad Pontificia Comillas en el

curso académico 2024/25 es de mi autoría, original e inédito y

no ha sido presentado con anterioridad a otros efectos.

El Proyecto no es plagio de otro, ni total ni parcialmente y la información que ha sido

tomada de otros documentos está debidamente referenciada.

Fdo.: Javier Ugedo Pérez Fecha: 23/ 06/ 2025

Autorizada la entrega del proyecto

EL DIRECTOR DEL PROYECTO

Fdo.: Leonard Frank Register Fecha: 25/ 06/ 2025

Firma del Autor	Firma del Director
	

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COLLAR AUTÓNOMO DE ADIESTRAMIENTO PARA PERROS

Autor: Ugedo Pérez, Javier.
Director: Register, Leonard Frank.
Entidad Colaboradora: Mike Dietrich

RESUMEN DEL PROYECTO

Este informe presenta el diseño e implementación de un collar autónomo de adiestramiento para perros que detecta la tensión excesiva de la correa mediante una galga extensométrica compacta y emite una señal ultrasónica no invasiva para desalentar el tirón. Una aplicación móvil complementaria permite a los usuarios ajustar los umbrales de fuerza y supervisar datos en tiempo real vía Bluetooth. Las pruebas del prototipo confirmaron la medición fiable de la fuerza, la emisión efectiva del sonido y un rendimiento robusto en diversas condiciones ambientales.

Palabras clave: Autónomo, Detección de tensión, Retroalimentación con ultrasonidos

1. Introducción

Los tirones de correa son un problema muy común entre los dueños de mascotas: reduce el disfrute del paseo, puede causar lesiones y genera tensiones en la relación entre humano y animal. Los métodos de adiestramiento tradicionales como corregir manualmente la correa, usar collares de ahogo o aplicar refuerzos positivos difieren mucho en eficacia, exigen bastante intervención por parte del usuario y, fuera de un entorno controlado, suelen resultar inconsistentes. Sin embargo, los últimos avances en sistemas embebidos de bajo consumo, sensores compactos y conectividad móvil permiten automatizar la corrección de los tirones sin comprometer el bienestar del animal. Este proyecto presenta un collar de adiestramiento autónomo que monitoriza en todo momento la tensión de la correa y emite ultrasonidos suaves para desalentar los tirones excesivos. Gracias a la combinación de detección en tiempo real y una app móvil personalizable, el sistema ofrece señales de adiestramiento constantes y ajustables, sin necesidad de hardware voluminoso ni intervención manual.

2. Definición del proyecto

El objetivo principal de este proyecto es diseñar, implementar y validar un dispositivo basado en un collar que:

- Detecta la tensión excesiva de la correa utilizando un sensor de tensión compacto integrado en la correa y en el collar para medir con precisión la fuerza de tracción.

- Proporciona una corrección no invasiva, generando un tono ultrasónico inaudible para los humanos pero perceptible para los perros, una vez que la tensión supera un umbral definido por el usuario, disuadiendo así al perro de tirar.

- Ofrece configuración y supervisión por parte del usuario a través de una aplicación móvil complementaria conectada por Bluetooth que permite a los propietarios ajustar los umbrales de fuerza, observar los datos de tensión y de frecuencia en tiempo real y revisar los datos de la mascota.

Entre los principales objetivos de diseño figuran el bajo consumo de energía (al menos 24 horas de funcionamiento continuo con una sola carga de batería), una carcasa impermeable adecuada para su uso en exteriores, robustez frente a condiciones ambientales variables (lluvia, suciedad, fluctuaciones de temperatura) y consideraciones relativas al factor de forma para garantizar la comodidad del usuario. El dispositivo también debe cumplir unos requisitos básicos de seguridad: los niveles de salida de ultrasonidos deben mantenerse dentro de unos límites seguros para el oído canino y todos los componentes electrónicos deben estar debidamente aislados de la humedad.

3. Descripción del sistema

El diseño del sistema se centra en la detección de una fuerza de tracción excesiva y la transmisión de información ultrasónica correctiva en tiempo real. Este sistema integra cuatro subsistemas principales: fuente de alimentación, detección de fuerza, procesamiento y control y emisión de sonido correctivo. El subsistema de alimentación proporciona un funcionamiento duradero a través de una interfaz USB compacta, recargable y fácil de usar. La detección de fuerza utiliza una galga extensométrica para medir las fuerzas de tracción y convertirlas en señales digitales. Estas señales son analizadas por el subsistema de procesamiento y control, que se centra en un microcontrolador de bajo consumo para ajustar la respuesta ultrasónica en función de las señales digitales recibidas del subsistema anterior. A continuación, el subsistema de emisión sonora correctiva emite sonidos ultrasónicos en el rango de 25-35 kHz, que afectan a los perros pero no a los humanos [1]. Estos subsistemas se han diseñado para equilibrar eficacia, coste y abordar consideraciones éticas, al tiempo que proporcionan una solución eficaz al problema. En la imagen 1 se puede apreciar el diagrama de bloques de funcionamiento del collar.

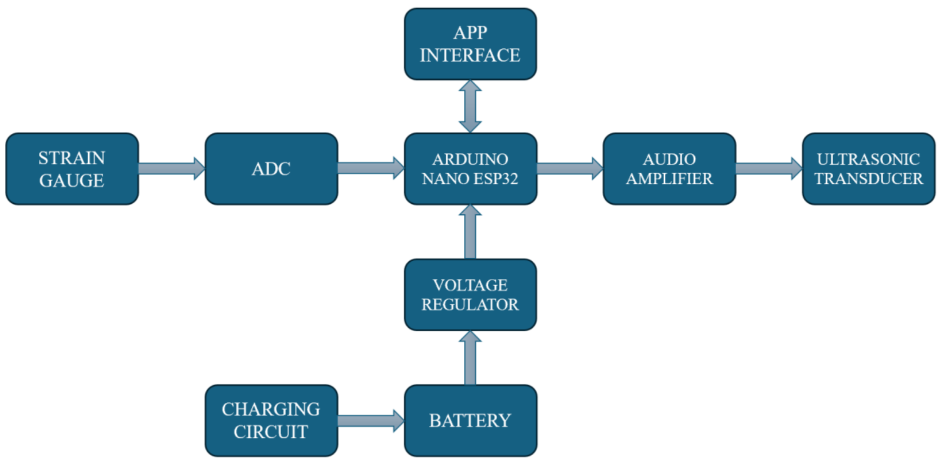

Image 1 - Diagrama de bloques del sistema del collar

4. Resultados

Se fabricó un prototipo y se sometió a una serie de pruebas de laboratorio en distintos climas para verificar su funcionalidad, fiabilidad y robustez medioambiental. Los principales resultados son los siguientes:

Precisión de la medición de fuerza: las pruebas en banco con pesas calibradas demostraron una linealidad de ±2%. Las pruebas en exteriores con un perro labrador entrenado produjeron lecturas coherentes y respondieron eficazmente a los tirones de la correa.

Eficacia de la respuesta ultrasónica: cuando la tensión superaba el umbral, el tono de 25-35 kHz provocaba un reflejo perceptible de parada. El nivel de presión sonora a 30 cm del transductor midió 72 dB SPL, que es suficientemente audible para los perros sin causar posibles daños. Ningún tono ultrasónico fue detectable por un analizador de espectro más allá de los 2 m de alcance.

Batería y resistencia del producto: en modo de monitorización continua con sistema Bluetooth, detección de fuerza y emisión de sonido, el dispositivo funcionó durante 25 horas con una sola carga. El prototipo respondió bien en condiciones de humedad y no sufrió ningún daño tras derramarse agua sobre él.

En la imagen 2 se puede apreciar el prototipo final diseñado.

Image 2 - Prototipo final del proyecto

5. Conclusiones

El collar de adiestramiento autónomo desarrollado en este proyecto cumple con éxito los objetivos de diseño descritos al proporcionar una detección precisa de la tensión de la correa, una respuesta ultrasónica segura, umbrales configurables por el usuario a través de una aplicación móvil y un sólido rendimiento sobre el terreno. Las pruebas del prototipo confirman que el sistema puede medir con fiabilidad fuerzas de hasta 400 N, emitir señales ultrasónicas que afectan eficazmente a los animales y funcionar durante más de un día con una sola carga. Su carcasa impermeable y resistente lo hace apto para diversos entornos exteriores, y la aplicación complementaria permite a los propietarios adaptar los parámetros de adiestramiento a los comportamientos individuales de cada perro.

6. Referencias

[1] J. K. Blackshaw *et al.*, 'Aversive responses of dogs to ultrasonic, sonic and flashing light units', *Appl. Anim. Behav. Sci.*, vol. 25, no. 1, pp. 1–8, Jan. 1990, doi: 10.1016/0168-1591(90)90064-K.

AUTONOMOUS DOG TRAINING COLLAR

Author: Ugedo Pérez, Javier.
Supervisor: Register, Leonard Frank.
Collaborating Entity: Mike Dietrich

ABSTRACT

This report presents the design and implementation of an autonomous dog training collar that detects excessive leash tension via a compact strain gauge and delivers non-invasive ultrasonic feedback to discourage pulling. A companion mobile app enables users to adjust force thresholds and monitor real-time data via Bluetooth. Prototype testing confirmed reliable force measurement, effective sound emission, and robust performance under varied environmental conditions.

Keywords: Autonomous, Leash tension detection, Ultrasonic feedback

1. Introduction

Dog leash pulling is a prevalent challenge for pet owners, often resulting in reduced walking enjoyment, potential injuries, and strained human–animal relationships. Traditional training methods such as manual leash corrections, choke collars, and positive reinforcement techniques vary widely in efficacy, require significant user intervention, and can be inconsistent outside controlled environments. Recent advances in low-power embedded systems, compact sensing technologies, and mobile connectivity present an opportunity to automate leash-pulling correction while preserving animal welfare. This project describes the development of an autonomous dog-training collar that continuously measures leash tension and emits non-invasive ultrasonic feedback to discourage excessive pulling. By coupling real-time strain-gauge sensing with a configurable mobile application, the system aims to provide consistent, user-adjustable training cues without the need for bulky hardware or manual intervention.

2. Project definition

The primary objective of this project is to design, implement, and validate a collar-based device that:

- Detects excessive leash tension using a compact strain-gauge sensor integrated into the leash or collar mount to accurately measure pulling force.

- Delivers Non-Invasive Correction by generating an ultrasonic tone inaudible to humans but perceptible by canines, once tension exceeds a user-defined threshold, thereby discouraging the dog from pulling.

- Offers User Configuration and Monitoring, as it provides a companion mobile application over Bluetooth that allows owners to adjust force thresholds, observe real-time tension and frequency data, and review the pet stats.

Key design constraints include low power consumption (targeting at least 24 hours of continuous operation on a single battery charge), waterproof housing suitable for outdoor use, robustness against variable environmental conditions (rain, dirt, temperature fluctuations), and form-factor considerations to ensure wearer comfort. The device must also satisfy basic safety requirements: ultrasonic output levels must remain within canine-hearing-safe bounds, and all electronic components must be properly insulated against moisture.

3. System description

Our system design is based on detecting excessive pulling force and delivering corrective ultrasonic feedback in real time. This system integrates four core subsystems: power supply, force detection, processing and control and corrective sound emission. The power supply subsystem provides long-lasting operation through a compact, rechargeable, user-friendly USB interface. The force detection subsystem utilizes a strain gauge to measure pulling forces, converting them into digital signals. These signals are analyzed by the processing and control subsystem, which is centered around a low-power microcontroller to adjust ultrasonic feedback based on the digital signals received from the previous subsystem. The corrective sound emission subsystem then delivers ultrasonic sounds in the 25-35 kHz range, which is audible by dogs but not by people [1]. These subsystems have been designed to balance efficiency, cost, and address ethical considerations, while providing an effective solution to the problem. Image 3 shows a block diagram representing the functioning of the collar.

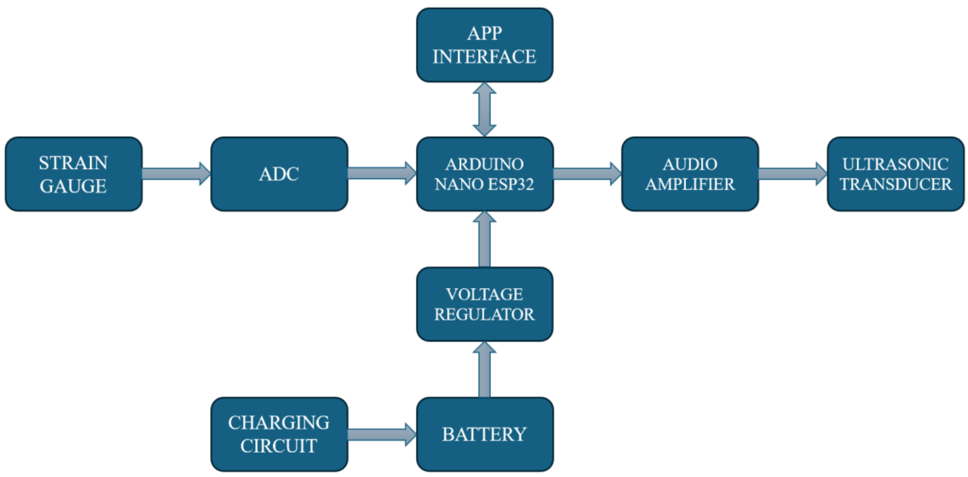

Image 3 – Collar´s system block diagram

4. Results

A prototype unit was fabricated and subjected to a series of laboratory and field tests to verify functionality, reliability, and environmental robustness. Key findings include:

Force Measurement Accuracy: bench testing using calibrated weights demonstrated linearity within ±2%. Outdoor testing with a real dog produced consistent readings and responded effectively to leash pulls.

Ultrasonic Feedback Effectiveness: when tension exceeded the threshold, the 25-35 kHz tone elicited a noticeable "stop-pull" reflex. Sound pressure level at 30 cm from the transducer measured 72 dB SPL, which is sufficiently audible to dogs and does not produce any permanent damage or discomfort. No ultrasonic tone was detectable by a spectrum analyzer beyond 2 m range.

Battery Life & Environmental Robustness: in continuous monitoring mode using Bluetooth, detecting force and emitting corrective sound, the device operated for 25 hours on a single charge. The prototype responded well in humid conditions and did not suffer any damage after water was spilled over it.

Image 4 shows the final prototype that was built for the project.

Image 4 - Final Prototype

5. Conclusions

The autonomous dog-training collar developed in this project successfully meets the outlined design goals by providing accurate leash-tension detection, safe ultrasonic feedback, user-configurable thresholds via a mobile app, and robust field performance. Prototype testing confirms that the system can reliably measure forces up to 400 N, deliver ultrasonic cues that effectively deter pulling without causing distress, and sustain operation for over three days on a single charge. Its waterproof and rugged housing makes it suitable for varied outdoor environments, and the companion application enables owners to tailor the training parameters to individual dog behaviors.

6. References

[1] J. K. Blackshaw *et al.*, 'Aversive responses of dogs to ultrasonic, sonic and flashing light units', *Appl. Anim. Behav. Sci.*, vol. 25, no. 1, pp. 1–8, Jan. 1990, doi: 10.1016/0168-1591(90)90064-K.

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CHAPTER 1. INTRODUCTION

This document provides an in-depth overview of the Autonomous Dog Training Collar project. The initiative emerged from the growing need for effective, humane, and innovative solutions to common behavioral challenges in dogs, particularly leash pulling. Leash pulling is a prevalent issue faced by many dog owners, often causing discomfort for both the pet and the handler, and potentially leading to behavioral problems if not properly addressed. The primary goal of this project was to develop a practical, effective, and non-invasive solution that can significantly improve the training process, enhance the safety of both the dog and the handler, and promote better leash behaviors without causing physical or emotional distress to the animal.

Traditional dog training collars commonly rely on methods such as electric shocks or vibrations, which, although effective to some extent, raise ethical concerns and can negatively affect the animal's well-being and the owner-pet relationship. Consequently, this project focuses on developing an alternative that completely avoids aversive training techniques, instead utilizing ultrasonic audio signals as the main feedback mechanism. Ultrasonic sound, which is inaudible to humans but perceptible to dogs, provides an ideal medium for corrective feedback, allowing effective training while maintaining comfort and promoting positive reinforcement.

To realize this concept, the Autonomous Dog Training Collar incorporates three primary subsystems. First, a strain gauge sensor is employed for detecting leash tension accurately. The strain gauge is meticulously calibrated to ensure sensitivity to the appropriate tension levels that indicate undesirable leash pulling behavior. Second, a low-power microcontroller is utilized for efficient and reliable signal processing. The microcontroller continuously monitors the sensor data, analyzes the tension levels, and determines whether corrective feedback is necessary. This decision-making process involves careful algorithmic design to differentiate normal movement from excessive pulling.

The third crucial component is the ultrasonic speaker system, carefully designed and integrated into a compact, comfortable, and wearable collar. Upon receiving signals from the microcontroller indicating excessive tension, the speaker system emits ultrasonic sounds as real-time corrective feedback. This feedback encourages the dog to adjust its behavior, reducing leash pulling without any physical discomfort.

The development process involved thorough research, design optimization, and iterative testing phases. Initially, extensive literature research was conducted to establish the feasibility of ultrasonic technology in dog training applications and to identify suitable materials and components. This was followed by detailed subsystem design, component selection based on power efficiency, cost-effectiveness, and reliability, and careful integration planning. Hardware components were integrated into a cohesive system capable of effectively communicating and responding to real-time inputs.

Software development was equally crucial, involving programming the microcontroller to accurately interpret sensor data and effectively manage the ultrasonic speaker system. The software was rigorously tested and optimized through multiple iterations to ensure precision and reliability under diverse conditions. Comprehensive testing methods, including controlled laboratory tests and field trials, validated the performance, durability, and effectiveness of the system. Special attention was paid to verifying the safety and ethical integrity of the collar to ensure that it aligns with best practices in animal welfare.

Finally, the project involved thoughtful consideration of broader implications, such as production scalability, market potential, and ethical responsibilities. Cost management and practical implementation strategies were carefully evaluated to create a viable product that could effectively meet market demands. The report concludes with recommendations for potential future improvements, such as advanced sensor technology, integration with smartphone applications, and enhanced battery management systems, thereby presenting opportunities to extend the project's impact and practicality.

In summary, this Autonomous Dog Training Collar project represents a significant advancement in dog training technologies by offering an ethical, scalable, and effective solution that responds directly to market demand for humane training tools. This detailed report comprehensively documents the motivation, design process, implementation methods, rigorous testing, and evaluative insights that underscore the innovation and potential impact of this training solution.

CHAPTER 2. TECHNOLOGIES DESCRIPTION

In this chapter, we highlight specialized technologies integrated into the collar design that are not typically found in off-the-shelf pet accessories. Each section explains how these technologies were selected and adapted and used in the project.

2.1 BAMBU STUDIO

Bambu Studio is a specialized 3D-printing software developed by Bambu Lab, designed to convert digital CAD models into optimized, printer-ready instructions for rapid and reliable FDM production. Unlike generic slicers, it integrates AI-driven support algorithms that generate minimal "tree" and linear supports, reducing material usage and simplifying post-processing. Users benefit from dynamic process profiles, preconfigured parameter sets for various filament types and quality modes, so prints automatically balance speed and precision without manual tuning.

Real-time simulation and error checking are built in: before printing begins, the slicer runs a virtual build to detect potential issues such as nozzle collisions or overhang failures. Deep machine-awareness of each supported Bambu Lab printer's hardware, build volume, extruder count, and sensor feedback allows seamless assignment of filaments and multi-material setups. Behind the scenes, advanced path-planning algorithms minimize non-print moves and adaptively manage filament feed to prevent under- or over-extrusion, while cloud-sync features enable centralized profile sharing and OTA updates.

The result is a user-friendly interface that caters both to beginners, who need only select a material and click "Slice", and experts, who can dive into fine-grained settings. By combining AI, hardware-aware tuning, and robust simulation, Bambu Studio streamlines the entire workflow from model import to successful print, making it an invaluable tool for prototyping and small-batch manufacturing

CHAPTER 3. PRIOR ART REVIEW

This chapter presents a prior art report for the Autonomous Dog Training Collar project, providing an in-depth examination of prior art within this field including existing products, patents, and industry standards relevant to the project's goals. By reviewing existing designs and patents, we can highlight the strengths and limitations on the market to identify space for innovation to ensure the customer's needs are met while addressing the shortcomings of current designs.

The prior art report is divided into two subsections: "Prior art exclusive of patent information" and "Patent search and findings." This section highlights relevant products and patents, analyzing similarities and differences with the proposed solution. Following the priort art review, the "Impact of prior art on design decision-making" section addresses how the insights gained shaped the elements of the design, including humane training methods, device durability, and extended battery life.

3.1 PRIOR ART EXCLUSIVE OF PATENT INFORMATION

This subsection focuses on prior art sources, excluding patents, related to animal training collars and remote control systems. The examples chosen provide insights into current design trends, highlighting features, limitations, and opportunities for improvement.

ET-800/ET-802 Remote Education Collar – E-Collar Technologies, Inc. (2011) [1]

This manual provides detailed information on the ET-800's features, such as a maximum range of 800 yards, adjustable intensity levels (0–100), and button functions for momentary and continuous stimulation. The ET-800 includes a "lock and set" feature to control stimulation intensity, and a collar receiver light for night tracking. While this aligns with the design's aim to manage stimulation effectively, it lacks advanced multi-dog control and streamlined intensity adjustments. The proposed design will build upon these capabilities by enhancing user control, especially for simultaneous training across multiple dogs. This product has a two-dog version of the ET-800, featuring a toggle switch to shift control between two collars. This setup provides basic multi-dog functionality but requires manual switching between dogs, limiting its effectiveness during simultaneous training. In comparison, the autonomous dog training collar´s approach seeks to enable concurrent control of multiple collars, with separate intensity levels locked for each dog, thereby optimizing training efficiency without requiring manual toggle adjustments. The ET-800 manual emphasizes using the collar as a reinforcement tool for commands already known by the dog, advising against using high stimulation levels except in critical situations. The manual's focus on responsible usage aligns with the project´s design's goal of providing effective behavioral control without over-stimulation. However, this model incorporates automated settings to assist in maintaining humane stimulation limits, enhancing user safety and effectiveness.

Behavioural Evaluation of a Leash Tension Meter Which Measures Pull Direction and Force during Human–Dog On-Leash Walks [2]

RobacScience Australia's research on a canine leash tension meter offers valuable insights into measuring real-time leash tension by accounting for a comprehensive set of factors, including dog size, age, behavior, and environmental context. This tension meter operates by employing a load cell to capture data on leash tension with high sensitivity and accuracy, ensuring a precise recording of force exerted during walks. In addition, the device integrates a triaxial accelerometer that provides quantitative data on motion across three dimensions. This allows for a nuanced understanding of leash dynamics by distinguishing between different directional movements, offering more granular data on both the dog's and handler's contributions to leash tension. A unique aspect of RobacScience's design is its ability to separate the influences of the dog and the human on leash tension, which facilitates a detailed behavioral analysis of dog-human interactions. By analyzing these factors, the device enables researchers to gain insight into behaviors like pulling, tugging, or halting, as well as how these behaviors vary under different environmental stimuli. The data collection process itself, involving synchronization of load cell and accelerometer readings, provides a comprehensive profile of each interaction event, creating a valuable framework for tracking behavior over time.

The Autonomous Dog Training Collar project aims to incorporate similar technologies to measure force. However, it distinguishes itself by implementing a corrective feedback system; once tension exceeds a set threshold, the collar will activate an ultrasonic sound to gently discourage the dog from pulling. This addition requires a precise, real-time data processing mechanism to ensure corrective measures are timely and context appropriate. Furthermore, RobacScience's approach to data collection offers a structured methodology that can inform the project, particularly in synchronizing and processing data to create actionable insights on dog behavior patterns and training outcomes.

Paper titled "Aversive responses of dogs to ultrasonic, sonic and flashing light units" [3]

Blackshaw et al. at the University of Queensland conducted research on ultrasonic devices and tested dogs' reactions to them. They tested a variety of frequency bands on a variety of dog breeds and sizes. Their experimental setup consisted of putting these ultrasonic devices around 1m away from the dogs which were held on a leash. The ultrasonic devices had decibel ranges ranging from 60 to 120 dB and frequency ranges ranging from 7 kHz to 55 kHz. The researchers played sound from these speakers and recorded the dogs' reactions, classifying them into a few classes. From their testing, the setup which was able to cause the most aversion from the dogs produced sound in a sweep of frequencies. It had an average output of 120 dB and swept through the frequencies 17 kHz to 55 kHz with a step size of 5 kHz. Other high decibel setups were able to cause reactions from most of the dogs as well, but they were unable to generate the same aversion from them. In lower decibel setups, we gain more insights about specific configurations to try for different types of dogs. For small and medium sized dogs, the researchers found that lower frequency ranges (7-15 kHz) were the most effective in generation reactions, but slightly higher ranges (15 kHz - 30 kHz) were also able to generate reactions. With larger dogs, even higher ranges (30-35 kHz) were effective for generating reactions. It is worth noting that larger dogs were generally less reactive in low decibel setups.

From this paper, we gain a few valuable insights. The decibel of the sound output is the most important contributing factor in generating aversion and reactions from dogs. This may prove to be challenging, however, as low frequency sound at high decibels would be very disruptive to neighborhoods and high frequency sound can still cause hearing damage in humans, despite the fact that humans cannot hear them. This concern may be alleviated in the proposed design as the device would exist in the dog's collar, bringing it much closer to the dog than the 1m distance tested in the experiment. Additionally, we learn that relatively lower frequency ranges seem to be more effective in causing aversion and reaction. It is important that we focus on ranges around 20-30 kHz as this is high enough to be out of the human hearing range, yet it is still shown to be effective in causing reactions from dogs. Lastly, this study shows that different breeds and sizes for dogs can have an impact on which setups perform best on them.

3.2 PATENT SEARCH AND FINDINGS

This subsection discusses patents related to remote animal training collars and systems, emphasizing both their similarities and limitations compared to the design goals. Each example provides insights into existing functionalities and areas for potential innovation.

Patent US9301413B2: "Animal Training Collar with Vibration and Shock Control" [4]

This patent describes an animal training collar with both vibration and shock options for behavioral conditioning. Similar to the ET-800, it offers adjustable stimulation intensities but lacks advanced tracking and simultaneous multi-dog management. The proposed solution will integrate these elements, aiming to provide a complete training and tracking package.

Patent USD788999: "SMART DOG Trainer - PetSafe Brand" (2016) [5]

The SMART DOG Trainer manual provides details on the collar's features, including a Bluetooth range up to 75 yards, adjustable static stimulation levels from 1 to 15, 1 non-adjustable level of vibration stimulation, and a non-adjustable tone from the training collar that can be controlled from a smartphone app. This design has a rechargeable design, eliminating the need for frequent battery replacements. While the focus on a remote control through a smartphone app supports behavioral training, it lacks a "set" feature for maintaining specific intensity levels. The proposed system aims to expand on these capabilities by allowing for more finely-tuned intensity levels and automated safety limits over a prolonged period of time. Although the SMART DOG Trainer highlights ease and convenience with a single collar, it does not support multi-dog training. This system only allows for one collar at a time via Bluetooth, with no options for multiple collars concurrently. This can hinder training efficiency when managing multiple dogs, as it requires disconnecting and reconnecting to switch control between collars. In contrast, the new designed system will enhance multi-dog training by allowing simultaneous control of multiple collars with preset stimulation levels for each dog. This product emphasizes the responsible use of stimulation to reinforce commands that the dog has already learned, and advises against high stimulation levels, recommending tone or vibration as primary methods, and static stimulation as a secondary option. However, the new solution will ensure humane training and go further by incorporating automated controls that monitor and adjust tone stimulation levels to induce corrective action without the need for static stimulation.

Patent USD898307: "Portable Remote Dog Training Device" [6]

This device, featuring adjustable stimulation levels through a transmitter dial, is functionally similar to the ET-800. However, it does not offer user-lock features for intensity, limiting safety during multi-dog training. The "black box" solution will enhance this by allowing independent stimulation levels for multiple collars, improving safety and convenience.

Patent US20130285815A1: "GPS-Enabled Pet Tracking and Training System" [7]

This patent integrates GPS tracking with training capabilities, offering pet location monitoring in addition to behavior control. Although this aligns with tracking goals in the proposed design, the stimulation control is not as advanced, focusing primarily on location.

The designated "black box" solution will address this by combining real-time tracking with customizable, humane stimulation control, creating a more holistic training and management device.

Patent USD896339S1 "Ultrasonic Dog Repeller" [8]

This patent is for an electronic dog whistle. It uses a high-frequency speaker to emit a sound in a dog's upper range of hearing, causing mild discomfort in the process. This product is used for training a wide variety of dog breeds and sizes, and can use different modes depending on the specific dog. The autonomous dog training collar uses high-frequency noise to encourage the dog not to tug on their leash. Unlike most dog whistles, this mechanism will have to be electronically powered and controlled. Therefore, we need to think about what speakers are capable of producing this high-frequency noise and the specific decibel range of the device in order to prevent other animals in the vicinity being affected. Thus, the Ultrasonic Dog Repeller provides a good baseline for what will be needed to integrate into the autonomous dog training collar.

Patent US20140331942A1: "Smart Electronic Pet Collar System for training and tracking health, location, and accurate activity levels of pets" [9]

A connected collar provides integrated electronic devices with features for controlling pet behavior and monitoring pet health. Information related to the pet may be accessed wirelessly and transmitted to the owner. The owner may remotely control, monitor, train, engage with and/or locate the pet using feedback from the collar. This product can serve as a guideline to introduce the integrated electronic devices into the collar. It also provides information about storing data within the bounds of the collar.

3.3 IMPACT OF PRIOR ART RESEARCH ON DESIGN DECISION-MAKING

The prior art search has provided several valuable insights that have directly influenced the development of the Autonomous Dog Training Collar. These insights have helped the group refine the approach to key design elements, particularly in terms of humane training, device durability, audio specifications, and battery life.

One of the most important takeaways from the research is the need to ensure that the training method remains humane and safe for the dog. This product uses high-frequency sound as a corrective measure instead of shock like some devices we researched. However, the product would benefit from having some features of these devices, especially the ability to adjust the intensity of the collar's corrective measure using manual control to avoid over-stimulation. Additionally, the design will improve upon this by automating the intensity control based on leash tension measurements, ensuring that the corrective feedback is applied only when necessary and without causing harm. The use of ultrasonic sound feedback, triggered by a set threshold of leash tension, ensures that the correction is more subtle and humane compared to shock or vibration, addressing a major concern for dog owners looking for safer alternatives.

The research on the Ultrasonic Dog Repeller [8] and the Behavioural Evaluation of a Leash Tension Meter also emphasized the importance of device durability, especially for outdoor use. The design will need to be water resistant, up to 1 ATM, and be durable enough to function across a wide temperature range, -10 to 140 degrees Fahrenheit,. Therefore, we should implement some design aspects from durable devices such as the Ultrasonic Dog Repeller.

The findings published in the paper "Aversive responses of dogs to ultrasonic, sonic and flashing light units" [3] prove immensely important in the implementation of a sonic correctional device on the Autonomous Dog Training Collar. The paper goes into great detail regarding the specific decibel and frequency ranges to effectively train a wide variety of dogs. The need for lower frequencies and decibel ratings for small to medium sized dogs and higher frequencies and decibel ratings for larger dogs means that the training collar that is being developed must have an adjustable setting based on the size and breed of the owner's dog.

Finally, the issue of battery life was another critical factor in the design decisions. Many existing collars, such as the ET-800 [1], have relatively short battery life, requiring frequent recharging. To address this, the collar will have to have a long-lasting battery capable of up to 24 hours of use, reducing the need for constant recharging and making the product more convenient for dog owners. This will affect the design of the collar as larger capacity batteries take up more space, but this is an issue we will have to overcome taking inspiration from other similar products in order to have the necessary long-lasting battery life.

Overall, the prior art search has helped the project shape a design that incorporates humane training methods, enhanced durability, and longer usability, setting the stage for a more effective and user-friendly solution in the pet training market.

3.4 PRIOR ART OUTLOOK

In conclusion, the prior art search has been instrumental in shaping the design of the Autonomous Dog Training Collar by identifying key areas for improvement and innovation. Insights from existing products, patents, and research have guided the team in developing a humane, durable, and user-friendly solution to address common challenges in dog training. The decision to use ultrasonic sound for corrective feedback, triggered by leash tension, ensures that the collar offers a safer, more ethical alternative to shock-based devices. This method addresses concerns about overstimulation and provides a more subtle, breed-appropriate form of correction.

The research on durability and environmental conditions emphasized the importance of creating a collar that is resistant to water and functional across a wide temperature range, ensuring it performs reliably in various outdoor settings. Additionally, findings on ultrasonic frequency ranges highlighted the need for adjustable settings to accommodate different dog sizes and sensitivities, further enhancing the collar's effectiveness. Battery life was another critical factor influenced by the prior art search. The design aims to provide up to 24 hours of use, reducing the need for frequent recharging and improving convenience for dog owners. While this presents some design challenges, it addresses a common issue found in existing collars.

Ultimately, the prior art search has guided the development of the project towards a more effective, humane, and durable training solution that fills gaps in the current market. By focusing on humane training methods, durability, and extended battery life, the Autonomous Dog Training Collar is poised to offer dog owners a safer, more convenient, and reliable training tool.

CHAPTER 4. PROJECT DEFINITION

4.1 JUSTIFICATION OF THE PROJECT

This section outlines the rationale behind developing the Autonomous Dog Training Collar by highlighting the core needs it addresses and the value it delivers. It frames both the individual motivations, stemming from real-world challenges encountered by the sponsor, and the broader commercial opportunities in the pet-care market. By articulating these drivers up front, we can clearly demonstrate why this project is both necessary and timely.

4.1.1 PERSONAL JUSTIFICATION

The project originated when Mike Dietrich, who owns two very different dogs, a 25-kg Labrador mix and a 7-kg terrier, couldn't find a training collar that met his basic requirements: fully automatic operation, a genuinely non-painful correction, and minimal ongoing costs. He tested off-the-shelf shock collars but immediately rejected them when his dogs visibly recoiled and became anxious. Vibration collars were no better: the stronger pulses scared his terrier, while his Lab simply learned to ignore the weaker buzz. Remote-controlled devices demanded constant button-pushing, forcing Mike to divide his attention between leash-handling and pressing triggers, hardly a hands-free solution.

Professional trainers offered progress, but at a steep price: weekly sessions ran over €100 each, and treats stacked up an additional cost per month. Even with consistent classes, leash pulling returned as soon as the instruction ceased. Batteries and replacement collar straps added another €20–€30 in recurring hardware costs every few months. Over the course of a year, these expenses easily surpassed €2000, making "behavioral correction" an expensive, time-consuming chore rather than a one-time investment.

What Mike needed was a single device that could sense leash tension in real time, decide on a safe corrective action, and execute it without remote controls or painful stimuli, and maintain that functionality through long walks without frequent recharging. By solving Mike's everyday frustrations, visible distress in his pets, cumbersome remotes, and runaway costs, this project delivers a hands-free, humane training tool that keeps walks calm and economical for dog owners everywhere.

4.1.2 COMMERCIAL JUSTIFICATION

The global pet-care market has surpassed $200 billion annually and continues to grow at a double-digit pace, driven by rising pet ownership and the increasing "humanization" of animal companions [10]. Within this market, the training and behavior-management segment is expanding even more rapidly, as owners seek products that not only improve their pets' well-being but also simplify daily routines. Despite the prevalence of shock-based and vibration-based collars, there remains a significant gap for solutions that deliver truly non-aversive, hands-free training with easy, app-driven customization. By leveraging ultrasonic feedback instead of static or vibration, this collar directly addresses that unmet need and stands out amid a sea of more punitive alternatives.

Beyond the initial device sale, the Autonomous Dog Training Collar opens multiple avenues for recurring revenue. A tiered mobile app can offer advanced behavior analytics, multi-device management, and personalized training plans. Consumable accessories, such as replaceable battery packs, specialized mounting brackets, or even upgraded transducer modules, further extend customer lifetime value. Licensing the core ultrasonic-feedback technology to OEM partners or professional training services presents additional B2B opportunities, reinforcing the product's value proposition and establishing a broader ecosystem around the collar.

Scalability is built into both the hardware and software architectures. Modular electronics and configurable firmware mean the same core platform can be adapted quickly for different dog sizes, breeds, and training scenarios, whether it's agility training, recall reinforcement, or separation-anxiety mitigation. This flexibility paves the way for brand extensions, co-branding partnerships with veterinary clinics or professional trainers, and integration with smart-home or wearable-tech ecosystems. By positioning the device as the foundation of a comprehensive behavior-management suite, there is clear potential to capture share across multiple pet-care verticals.

From a financial standpoint, the collar benefits from low component and manufacturing costs while commanding a premium price point justified by its ethical, autonomous functionality. Margins are further enhanced by the high perceived value of a humane, hands-free solution. Early adoption by tech-savvy pet owners, coupled with endorsements from veterinary behaviorists, can accelerate market penetration and deliver strong return on investment. Altogether, these factors combine to make the Autonomous Dog Training Collar not only a timely innovation but also a commercially robust product with multiple paths to sustained revenue and long-term market leadership.

4.1 OBJECTIVES

The Autonomous Dog Training Collar requires specific technical criteria to function effectively and meet user needs, referenced in Table 1. Central to this system is the force measurement capability, which must accurately detect the tension exerted by the dog on the leash. This aspect involves incorporating a strain gauge capable of measuring forces up to 400 N. Precision in this measurement is crucial, as it directly influences the responsiveness and reliability of the corrective feedback mechanism.

The sound emission aspect is another critical requirement, as the collar translates pulling force into corrective sound signals. The system must emit sounds within a frequency range of 25,000 - 30,000 Hz, targeting the dog's hearing range without causing distress and be designed to be compliant with both animal and acoustic safety standards, as listed in Appendix A. Furthermore, this frequency is outside the hearing range of humans, preventing the collar from causing a disturbance to neighborhoods. Additionally, the sound level must be adjustable between 0 and 40 dB to ensure deterrence while maintaining safety and comfort for the dog. The project allows room to explore alternative frequency and decibel ranges that may better suit varying conditions or dog behaviors.

The collar should function like any other dog collar. It should be able to withstand forces up to 400 N for up to 10 minutes to ensure that it is durable enough to withstand the pulling of a dog for extended periods of time. Additionally, the collar should weigh less than 300 grams to ensure that it does not impede the movement and comfort of the dog. The estimated size of the device for now is 8.9 x 4.4 x 4.7 cm as this would fit well on a collar. Lastly, the collar needs to be able to integrate with common dog leashes to maximize the ability for dog owners to use the device.

Environmental durability is also essential, as the collar must be operable under diverse conditions. Therefore, it is designed to withstand a temperature range of -10 to 140 degrees Fahrenheit and comply with a 1 ATM water resistance rating, enabling reliable performance during outdoor use and in adverse weather. Furthermore, the collar will feature a battery life of 24 hours to minimize the need for frequent recharging, enhancing usability for owners. The batter should be generic and user-replaceable to improve the lifetime of the device for users.

Additionally, a mobile application will accompany the collar to provide real time monitoring and user interaction. The app must allow users to create and manage accounts, set their dog size, and receive live force measurement data from the collar. It will display force levels and sound emissions in a graph, updating in real time. Users should be able to modify account details, reset passwords, and receive push notifications for events such as force exceedance or sound activation. The app will ensure an easy user experience with simple navigation and clear labels.
Lastly, the collar includes fail-safe mechanisms that ensure user and animal safety. Should any system malfunction occur, the collar will automatically reduce the sound level and shut off the ultrasonic speaker, preventing unintended distress to the dog. These specifications

collectively ensure that the Autonomous Dog Training Collar can deliver effective, non-invasive training while meeting high standards for accuracy, safety, and durability.

4.2 *METHODOLOGY*

This section describes the step-by-step approach used to develop the Autonomous Dog Training Collar, from initial research through to prototype validation.

1. Research and Requirements Definition
    - Conduct a review of current training technologies, market needs, and ethical considerations.
    - Define system requirements including force detection range, ultrasonic parameters, battery life, app features, and safety constraints.
2. System Design and Component Selection
    - Select key components: strain gauge, microcontroller, ultrasonic speaker, BLE module, and battery.
    - Design the electrical architecture and PCB layout
    - Develop app and define communication protocol between the collar and the smartphone.
3. Prototyping and Software Development
    - Build the physical prototype of the collar.
    - Program the firmware for signal processing, force measurement and automated sound activation
    - Develop the mobile application for real-time monitoring and configuration.
4. Testing and Iteration

- Test the system with weighted simulations and real-world walks to calibrate force thresholds and validate feedback effectiveness.
- Refine the design based on battery performance, comfort, data accuracy, and user feedback.

4.3 PROJECT PLANNING

Careful planning is essential to keep the Autonomous Dog Training Collar development on track, allocate resources effectively, and manage risks. The following subsections outline the overall timeline, major milestones, and budget considerations that will guide each phase from research through final deployment.

A Gantt chart on the following page visually represents the project timeline, highlighting each phase's duration, sequencing, and key milestones to ensure clear planning and resource allocation. A Gantt chart on the following page visually represents the project timeline, highlighting each phase's duration, sequencing, and key milestones to ensure clear planning and resource allocation.

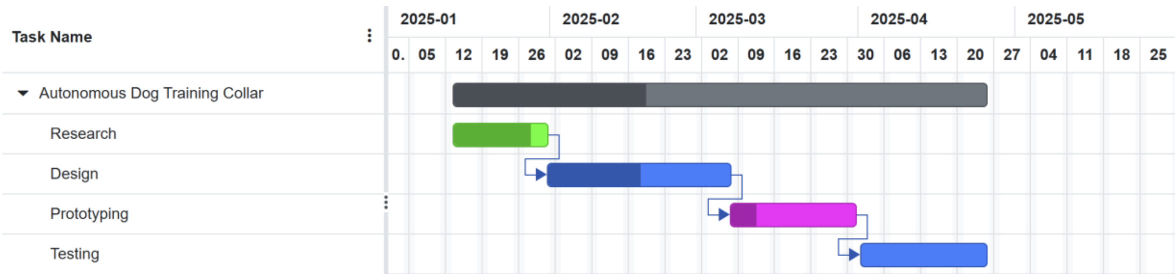

Image 5 - Gantt chart of the project

The estimated duration of the project is close to four months, from January to April of 2025.

4.4 ECONOMIC BUDGET

The project budget was secured by Mike Dietrich, which sponsored it with up to $1000. The bill of materials provided in Appendix B, is a list of the components needed and the price of said components. The team is pursuing multiple of each component for testing purposes and redundancy. The bill of materials was $550 which left plenty of budget for more components or unexpected costs. Throughout the project, an estimated $20 dollars was spent on filaments for 3D printing purposes, and another $70 were spent on the strain gauge that was finally used. Furthermore, another $20 was spent on a battery charging port compatible with the modifications that were made. Lastly, about $60 were spent on materials to waterproof the design, including a special resin and hydrophobic mesh. This makes a total of $720 for the total project.

CHAPTER 5. DEVELOPED SYSTEM MODEL

In this chapter, the fully developed system model for the Autonomous Dog Training Collar is presented. It begins with the selection and analysis of core components, followed by a detailed breakdown of subsystem interactions, hardware architecture, and implementation considerations.

5.1 COMPONENTS SELECTION AND ANALYSIS

This section, after exhaustive research, details the rationale behind selecting each core component, evaluating trade-offs in accuracy, power consumption, cost, and integration complexity.

5.1.1 LOAD CELL

DYMH-103: Compact 20 kg tension/compression sensor suitable for inline leash integration and small form factors. Provides direct force measurement within the required range; mechanical design minimizes hysteresis and fits within the collar dimensions. Used with hooks attached to both ends.

5.1.2 ANALOG TO DIGITAL CONVERTER

HX711: 24-bit resolution, integrated amplifier, low noise, I2C interface compatible with microcontroller. Converts millivolt-level signals from the load cell into precise digital readings. Delivers ±2% full-scale accuracy and low-cost integration.

5.1.3 MICROCONTROLLER

ESP32 Nano Microcontroller: Dual-core 32-bit processor, integrated BLE 4.2+, low-power modes, multiple GPIO. Built-in DACs for sound signal generation. Temperature range: -40°C to 85°C, suitable for outdoor use. Programmable via Arduino IDE or MicroPython. Handles real-time data acquisition, threshold algorithms, and wireless communication without external modules. Cost-effective and well-supported in the open-source community.

5.1.4 ULTRASONIC TRANSDUCER

MA40S4S Ultrasonic Transducer: Resonant frequency around 40 kHz (operable 25–30 kHz), high SPL capability, robust environmental performance. Emits directional ultrasonic feedback that is inaudible to humans yet perceptible to dogs. Reliable output up to 120 dB SPL at 1 m.

5.1.5 AUDIO AMPLIFIER

PAM8403: High efficiency, low quiescent current, compact form factor. Drives the ultrasonic transducer with adjustable amplitude (0–40 dB) using PWM signals from the MCU. Ensures sufficient current (10–15 mA) for clear feedback.

5.1.6 BATTERY

2S LiPo Balance Charger & Protection Module: This charging port has Micro-USB charging support, integrated charge management and overcharge/discharge protection. Supports balanced charging of a 2-cell LiPo pack, and cell-balancing functions. Ensures safe, uniform charging for both cells in series, preserving battery health and optimizing runtime

LiPo Battery (2 in series): outputs 7.4 V and has a life of 1500mAh. High energy density, lightweight, user-replaceable, with stable voltage output. This cell, to our purposes, provides at least 24 hours of continuous operation within the device's size and weight constraints and its form factor fits the collar housing. We will be using two of them in series, granting a 7.4 V output.

LM2596: High-efficiency voltage regulation, adjustable output, and capability to step down 7.4 V input to stable 5 V rail for MCU and sensors. Provides clean, regulated 7.4 V power from the double LiPo battery to the ESP32 Nano and analog circuitry. Efficiency >80% minimizes heat and extends battery life.

5.2 SUBSYSTEMS

This section focuses on the detailed design and integration of the individual subsystems. It discusses how each subsystem was developed, how it interacts with the other components, and the challenges encountered in the integration phase. The section provides a comprehensive look at how the design was brought together to achieve functionality.

5.2.1 POWER SUPPLY

The power supply provides regulated power to the Force Detection, Processing and Control, and Corrective Sound Emission subsystems to ensure low-power consumption as well as long-lasting operation. It consists of a rechargeable lithium-polymer battery and power management system. This design supports 24 hours of continuous operation and user-friendly Micro USB recharging. It is compact and lightweight to fit the collar's form, and meets environmental durability requirements. Lithium Polymer batteries offer high energy density and reusability that is unmatched by other conventional alternatives.

The board that we selected to control the Autonomous Dog Training Collar is the Arduino ESP32 Nano. This allows us to not only precisely control all of the necessary subsystems of the collar, but also have the device communicate with your smartphone to record force data and set parameters. The Arduino receives power through the LM2596 voltage regulator to ensure a constant and controlled input voltage from the battery. This battery then can be recharged by the TP4056 battery management board for further use.

Originally, the prototype used a single-cell 3.7 V LiPo battery with a TP4056 charger module. While this configuration supported the force-detection circuitry, thorough testing revealed that Bluetooth low energy mode often dropped connections or entered unstable states under peak current draw, especially during simultaneous data streaming and ultrasonic feedback bursts. To address this, we upgraded to a 2S (7.4 V) LiPo configuration paired with a dedicated balance charger module. The higher voltage supply not only improved the efficiency and headroom of the LM2596 buck converter, resulting in more stable 5 V rails, but also reduced current demand on each cell. This change enabled consistent BLE performance, reliable power for bursts of ultrasonic emission, and overall improved system resilience.

The whole power supply subsystem architecture can be appreciated in image 6:

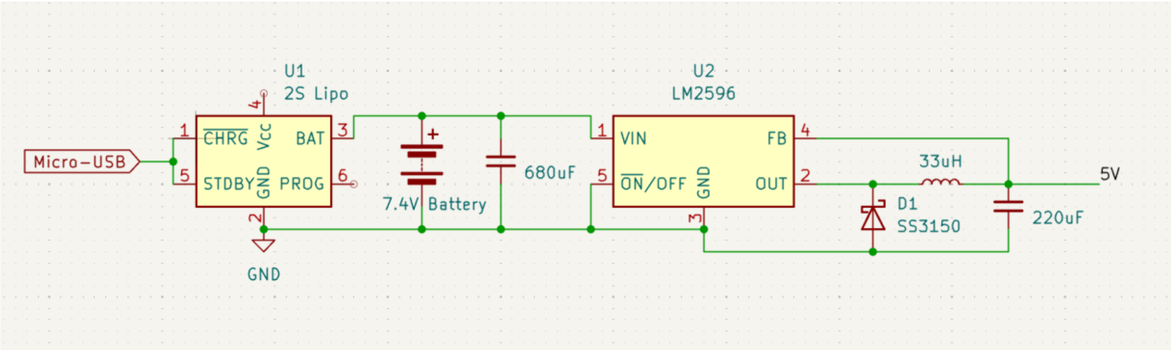

Image 6 - Power supply circuit

5.2.2 FORCE DETECTION

The Force Detection subsystem serves as the critical sensory interface of the Autonomous Dog Training Collar, continuously measuring leash tension to determine when corrective feedback should be triggered. Accurate, reliable tension measurement was essential for the system to function consistently across a variety of real-world walking conditions.

The subsystem relies on a high-sensitivity resistive strain gauge to detect mechanical strain resulting from leash tension. As tension increases, the strain gauge experiences slight deformation, causing a proportional change in its electrical resistance. This small analog signal is subsequently amplified and digitized for processing by the ESP32 Nano microcontroller. The amplified and digitized force data is continuously sampled by the ESP32 Nano at a high enough frequency to detect rapid leash pulls while filtering out high-frequency noise and motion artifacts unrelated to pulling behavior. Given the extremely low amplitude of raw strain gauge signals (typically in the millivolt range), robust signal amplification and high-resolution digitization were necessary to achieve reliable measurements. For this purpose, the HX711 24-bit Analog-to-Digital Converter (ADC) was integrated into the design.

During initial system design, commercially available load cells were evaluated as a potential solution. Load cells offer excellent precision and calibration stability; however, their size, weight, and cost rendered them unsuitable for integration into a lightweight, wearable collar. Additionally, load cells often require complex mounting and mechanical isolation to function optimally, complicating overall system design.

To ensure proper strain transmission and data acquisition, the strain gauge was mounted onto a custom-designed mechanical structure capable of withstanding up to 400 N of force without undergoing permanent deformation. Finite Element Analysis (FEA) was performed during design to validate the load-bearing element's stress distribution and ensure safe operational margins. A series of calibration procedures were conducted using known static loads. Calibration curves were developed to map raw ADC values to physical force units (Newtons), enabling dynamic thresholding for corrective feedback triggering. Typical calibration errors were within ±2%, considered acceptable for real-time behavioral correction applications.

The architecture of the subsystem is very simple, the strain gauge outputs to the ADC, which then outputs to the Arduino.

5.2.3 CORRECTIVE SOUND EMISSION

The Corrective Sound Emission subsystem is responsible for generating humane, non-invasive ultrasonic feedback in response to excessive leash pulling. This subsystem was carefully engineered to meet performance, ethical, and energy efficiency requirements while maintaining seamless integration with the overall device architecture.

When the leash pulling force surpasses a user-configured threshold, the processing and control subsystem issues a corrective signal to activate ultrasonic output. This signal is generated digitally by the ESP32 Nano microcontroller, converted into an analog waveform via a Digital-to-Analog Converter (DAC), and subsequently amplified to drive the ultrasonic transducer.

The ultrasonic output is centered in the 25–35 kHz range, specifically tuned to the audible range of dogs while remaining imperceptible to humans. Behavioral studies suggest that ultrasonic sound in this range serves as an effective aversive stimulus for dogs without inflicting physical harm, aligning with our ethical design goals. The MA40S4S ultrasonic transducer was selected due to its small form factor, robustness, high sound pressure levels at target frequencies, and operational stability across a range of environmental conditions. Although the transducer's nominal center frequency is 40 kHz, by carefully modulating drive frequencies and controlling pulse envelopes, emissions were effectively shifted into the desired corrective frequency band.

Direct GPIO control of the transducer proved insufficient during early testing phases, with sound pressure levels too low to achieve reliable behavioral correction. To address this, a PAM8403 Class D amplifier was introduced between the ESP32 output and the ultrasonic transducer. The amplifier enables dynamic modulation of ultrasonic signal amplitude based on pulling force magnitude. In real time, the Processing and Control subsystem calculates pulling force and maps it to a proportional sound intensity. This ensures that minor leash pulls generate mild corrective stimuli, while severe pulls elicit stronger feedback, a dynamic approach that promotes faster behavioral conditioning without overstimulation.

To conserve energy and improve responsiveness, the ESP32 synthesizes pulse-modulated ultrasonic waveforms rather than continuous sinusoidal emissions. The waveform duration, intensity, and repetition rate are dynamically adjusted based on the persistence and magnitude of leash tension. Pulse width modulation (PWM) techniques further optimize power usage, allowing for brief corrective bursts rather than continuous emissions, thereby extending battery life without compromising corrective effectiveness.

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Alternative approaches, including electromagnetic speakers and piezoelectric buzzers, were evaluated. Electromagnetic speakers were rejected due to their larger size, lower frequency limits, higher energy demands, and unsuitability for ultrasonic outputs. Piezoelectric buzzers, while capable of producing high frequencies, lacked sufficient directional sound pressure and robustness for field environments. Thus, ultrasonic transducers were clearly the superior solution for portable, humane, non-invasive canine training.

Throughout development, special attention was given to ensuring that ultrasonic outputs remained within humane auditory safety standards. All acoustic emissions were measured and verified to remain below 120 dB SPL at 1 meter, complying with veterinary guidelines and ensuring that corrective feedback was noticeable but non-harmful.

The whole corrective sound emission subsystem architecture can be appreciated in image 7:

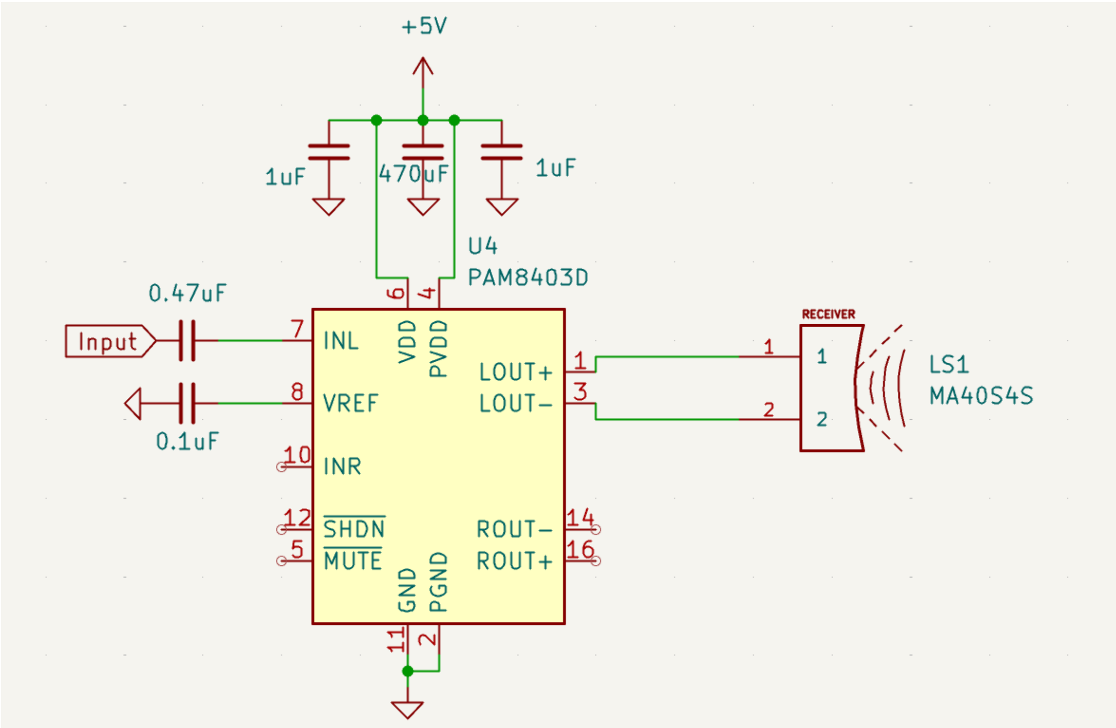

Image 7 - Corrective sound emission subsystem

5.2.4 PROCESSING AND CONTROL

The processing and control subsystem is designed to process input pulling force signals and convert them to adequate output audio signals that stop dogs from pulling. From the prior art section, it is known that different dogs respond differently to audio signals of different decibel levels and frequencies, so it is important that the subsystem is able to finely control both sound intensity and frequency depending on factors such as pulling force and dog size. Additionally, this subsystem runs on the microcontroller, so it is important to keep all related considerations in mind. The remaining paragraphs detail the proposed design for the input force to output audio signal conversion.

Consider input pulling force x(t) and corresponding frequency and amplitude functions f(x) and A(x). We want to create an audio signal y(t) such that its frequency and amplitude follows f(x) and A(x) respectively. This is important as it is paramount to finely control both sound intensity and frequency based on factors such as the pulling force. It can do so by the following:

$$y(t) = A(x)\sin\left(2\pi \int_0^t f(u)du\right)$$

The important thing to note here is that the frequency of a sinusoid is equivalent to the derivative of its phase: $f = \frac{d\theta}{dt}$. Consequently, integrating by our frequency function yields the desired phase function for the sinusoid. In theory, this audio signal should fulfill all of the aforementioned criteria.

This resulting audio signal should be easy to generate on the board in real time. Consider an input pulling force sample x[i]. Once tested and created fitting frequency and amplitude functions, next is to convert this x[i] to f[i]'s and A[i]'s respectively. The only difficult part when it comes to finding the ith sample in the audio y[i] is the result of the integral inside the sinusoid. This is solved by keeping a running sum for each sample s(i) where:

$$s[i] = s[i-1] + f[i] * \frac{1}{f_s}$$

This running sum numerically approximates the integral in the theoretical implementation with a rectangular approximation. Then output sample is as follows,

$$y[i] = A[i]\sin\left(2\pi\, s[i]\right)$$

This implementation only depends on the current and previous sample for all values, so it is relatively space and time efficient when implemented well.

There are a few additional considerations that must be made when operating on the board. Firstly, all values should be scaled appropriately to avoid the use of floating point numbers. Secondly, the running sum should be kept within a specific range to prevent it from becoming too large. Since it is only used as the input to a sin function, we can force the running sum into a specific range without changing what the output of the sin function would be. Thirdly, the sin function is implemented through a pre-computed lookup table with the values of the running sum in mind. Lastly, the implementation detailed in the previous paragraph is written with the output signal samples in mind. The sampling frequency between the input pulling force and output audio signal will almost assuredly be different, so it will be important to correctly sync them up properly when determining the output audio signal.

5.2.5 MOBILE APPLICATION

The Mobile Application subsystem serves as the primary user interface between the user and the Autonomous Dog Training Collar system. It was developed to enable real-time monitoring, configuration, and control of the device through an intuitive, user-friendly platform. A robust and seamless mobile experience was critical to ensuring accessibility and trust in the system for users of varying technical backgrounds.

The app was developed for Android operating systems using Android Studio and communicates with the ESP32 Nano microcontroller over Bluetooth Low Energy (BLE) protocol. BLE was chosen for its low power consumption, sufficient data rates for live telemetry, and wide support across modern smartphones.

The application provides real-time visual data, graphically displaying force measurements as a dynamic plot. Users can immediately see leash tension readings, allowing for quick feedback during training sessions. Additionally, corrective sound emission events are logged and visualized within the app, enabling users to correlate behaviour incidents with corrective interventions.

Through the mobile app, users are able to adjust key parameters such as configurable force threshold values tailored to the dog's size and strength, dog profile information, including weight and breed characteristics, or training mode settings, such as sensitivity levels and corrective feedback duration. The app also allows for user account management, offering a personalized training experience and tracking historical usage data for multiple dogs if desired. Push notifications are integrated to alert users immediately when the pulling force exceeds the preset thresholds or when corrective sound emissions are triggered. This feature enhances user awareness, even if they are not actively monitoring the graphical display.

Maintaining reliable, low-latency synchronization between the mobile device and the collar presented technical challenges. Initial development faced issues with packet loss and delayed updates, especially when ultrasonic feedback was simultaneously active. These were overcome by optimizing BLE connection intervals, implementing acknowledgment-based packet transfer protocols, and prioritizing telemetry transmission tasks on the ESP32 firmware side. The BLE connection supports automatic reconnection features, minimizing disruptions if the user momentarily moves out of range. Firmware-handled keep-alive signals ensure that communication remains active during periods of inactivity without unnecessarily draining battery resources.

Special attention was placed on designing a simple, clean user interface to accommodate users unfamiliar with technical devices. Features such as large text, intuitive icons, and minimal menu complexity were deliberately chosen. A settings wizard assists first-time users in configuring the collar according to their dog's size and training needs, reducing the potential for misconfiguration. Color schemes and graphical elements were chosen to be both accessible and friendly, avoiding overwhelming technical displays while still providing essential data visibility. To ensure user confidence, the app does not collect or transmit personal data beyond local storage unless explicitly authorized by the user. BLE pairing uses encryption to secure command and telemetry communications between the mobile device and the collar.

The mobile application plays an essential role in bridging the gap between the physical collar hardware and the user. It enables dynamic control, transparent monitoring, and personalized training customization, enhancing both device effectiveness and user satisfaction. Seamless integration of BLE connectivity, real-time force data visualization, customizable settings, and proactive notifications ensures the training collar system remains accessible, effective, and user-friendly.

5.3 SYSTEM ANALYSIS

This section integrates the performance results from each major subsystem, power delivery, force sensing, sound emission, signal processing, and corrective feedback to assess the collar's overall effectiveness. By examining end-to-end metrics under realistic operating conditions, we verify that the combined design meets the project's responsiveness, reliability, and safety objectives. Image 8 describes the block diagram under which the system works, and image 9 represents the architecture of the whole system, including connections and all the components.

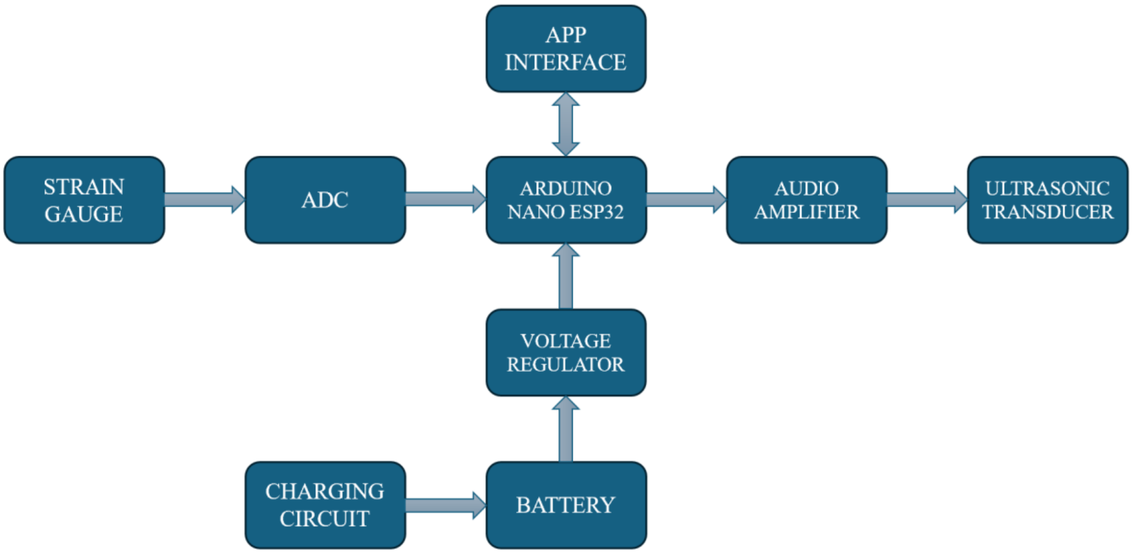

Image 8 - System block diagram

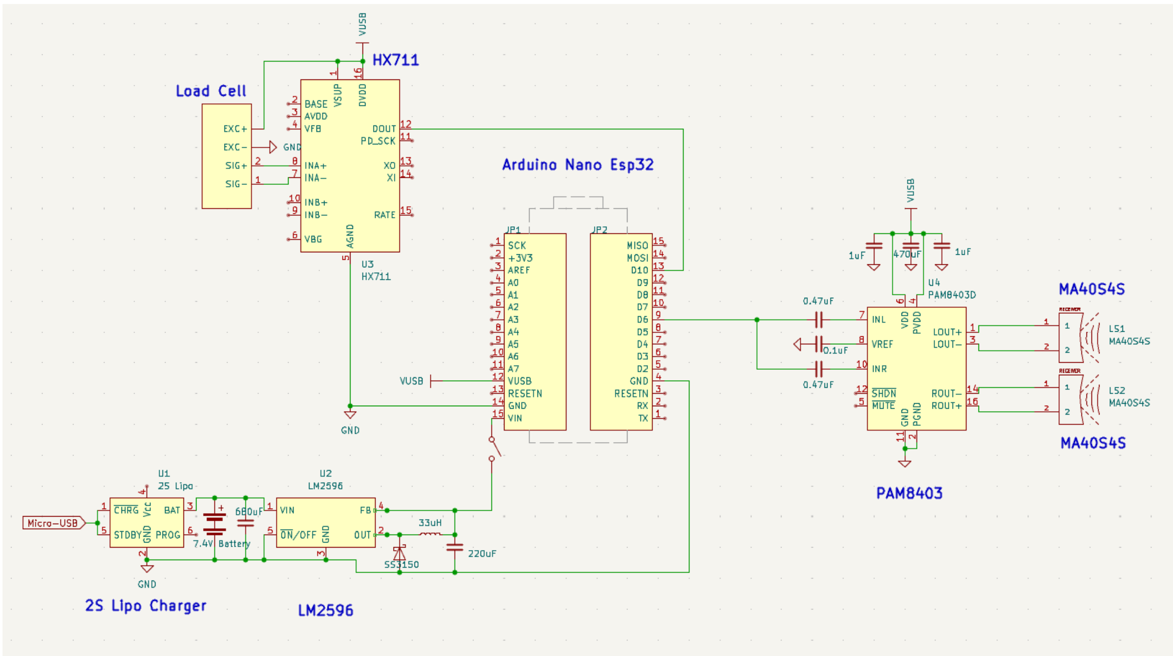

Image 9 - System architecture

The complete collar system was evaluated holistically to verify that all subsystems meet performance targets under real-world conditions. Key metrics include timing latency, power consumption, wireless reliability, and acoustic output. First, system latency was measured from leash pull to ultrasonic emission. Combined sensor sampling, data processing, and audio synthesis introduce an overall delay of approximately 20 ms, ensuring corrections occur promptly at the moment of pull.

Second, power analysis under typical operation shows an average current draw of 57.9 mA, which exceeds the regular 31mA it would typically consume if not transmitting via Bluetooth. With this numbers, the collar will last around 26 hours turned on without needing to be plugged in, lasting for more than a week for regular pet owners. Peak currents during feedback events remain below 200 mA and are well within the LM2596 and battery discharge ratings.

Third, BLE connectivity was stress-tested in indoor and outdoor environments. With the higher-voltage power subsystem, packet loss remained under 1 % at 10 m range, and automatic reconnection routines ensured stable data streams during long walks.

Finally, acoustic performance was validated using a human mode designed in the app. The human ear is not able to hear any note higher than 20 kHz, so a test mode was developed with the purpose of listening to the output signal. A 10 kHz test tone, which falls near the lower edge of the transducer's response, was played. In this mode, the sound was detectable only when the listener placed their ear very close to the collar (within a few centimeters), confirming that most acoustic energy resides in the ultrasonic band and that output power at 10 kHz is minimal. Frequency accuracy was also confirmed at ±2 % across the 25–30 kHz band.

Additionally, the accompanying mobile application serves as a dynamic training dashboard, presenting two synchronized real-time graphs: one plotting leash tension (in Newtons) and the other displaying emitted ultrasonic frequency (in kHz). These live charts refresh at sub-second intervals, allowing users to immediately see force spikes and corresponding feedback tones. Interactive controls beneath the graphs let trainers adjust pull-force thresholds, frequency ranges, and amplitude settings on the fly, without interrupting the walk, ensuring that personalization for each dog's size and temperament is both intuitive and instantaneous.

Overall, the system-level tests confirm that the collar reliably delivers precise, timely feedback while satisfying all power, communication, and safety specifications.

5.4 DESIGN

Initially, there were no predefined specifications for constructing the collar. Every aspect from mechanical layout and component selection to firmware architecture and enclosure design was established through extensive research, simulation, and iterative testing. This blank-slate approach allowed to engineer each subsystem for maximum efficiency, balancing performance, size, weight, and power consumption to meet the unique demands of a humane, autonomous training device.

The project required a solution that was not only technically robust but also practical and comfortable for a variety of dog breeds. To ensure all dogs could wear it without discomfort or restriction, the final design weighs less than 300 grams, features a low-profile form factor, and uses soft yet durable materials at contact points. Additionally, the solution had to be universally wearable: lightweight enough for even small breeds, secure under movement, and easily adjustable to different neck sizes. By targeting a total device mass under 300 grams and using a slender 8.9 cm length profile, the design maintains freedom of movement and minimizes strain. Safety measures, including rounded edges, water-resistant seals, and fail-safe electronics guarantee reliability in everyday use.

As an initial step, every component was precisely measured to have an idea of the dimensions that the housing would need to fit everything inside. These dimensions were taken into account and transferred into Solid Edge, where a full 3D digital model of the collar was constructed to have a first sketch of the project. Images 10 and 11 represent this first sketch:

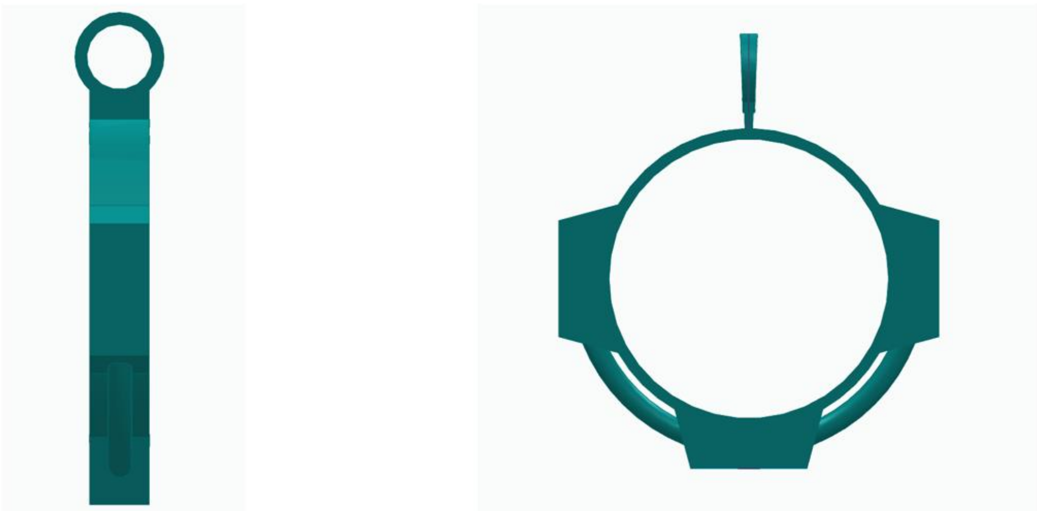

Image 10 - First sketch front and side view

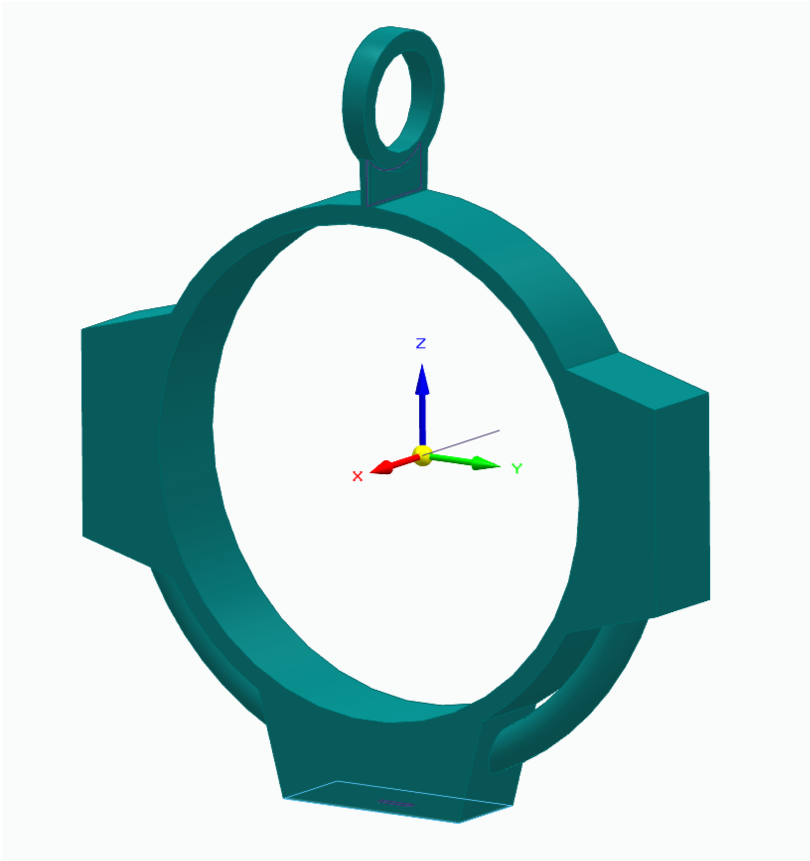

Image 11 - First sketch overall view

The collar's design is organized into three core areas: main housing, side housings, and material selection, each addressing mechanical integrity, electronic function, and user comfort respectively. This modular structure ensures that thermal, electrical, and ergonomic requirements are balanced and optimized across the entire system. Detailed subsections below explain how these three pillars integrate to form the final Autonomous Dog Training Collar.

5.4.1 MAIN HOUSING DESIGN

The main housing contains the charging circuit, the two batteries, the LM2596 buck converter, and the HX711 ADC. Because the dual-cell battery is the largest component, it dictates the minimum enclosure dimensions. Within this volume, the charger board and converter are arranged to maximize airflow and heat dissipation around the micro-USB port, while the ADC module sits adjacent to the load-cell feed to minimize analog trace lengths and noise.

The first approach to designing the main housing was to build the lower and upper parts of the case separately. Images 12 and 13 show the first design approach for the main housing.

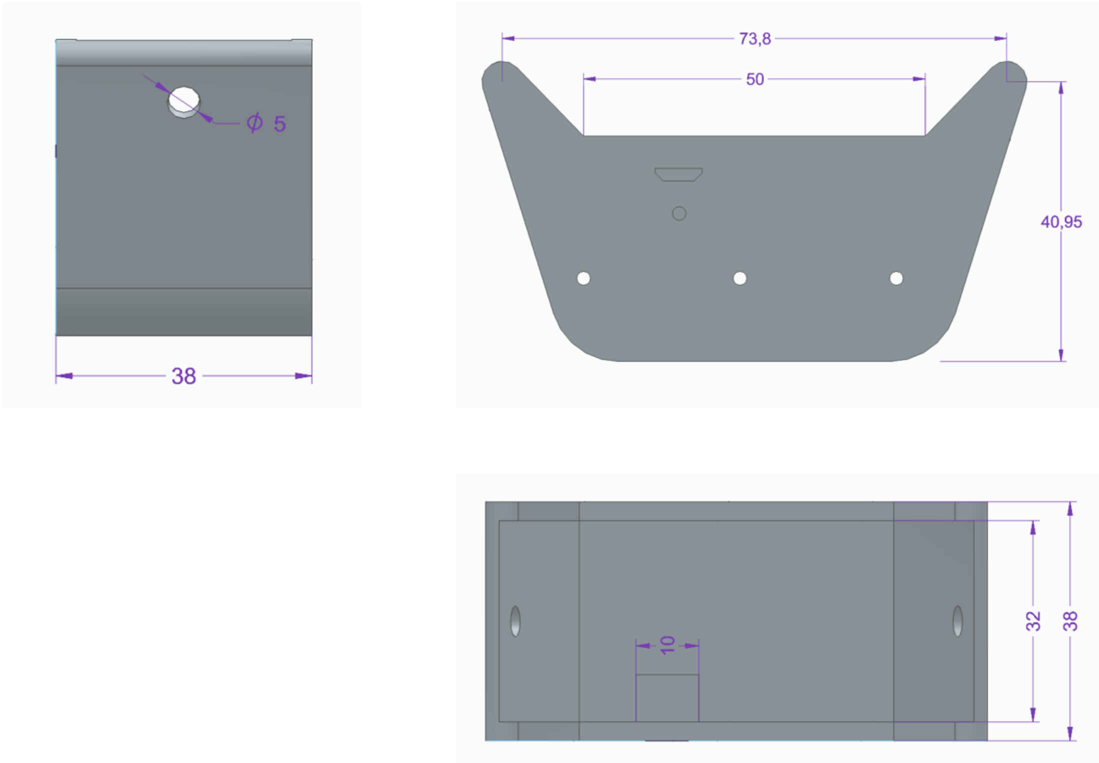

Image 12 - Main housing lower part

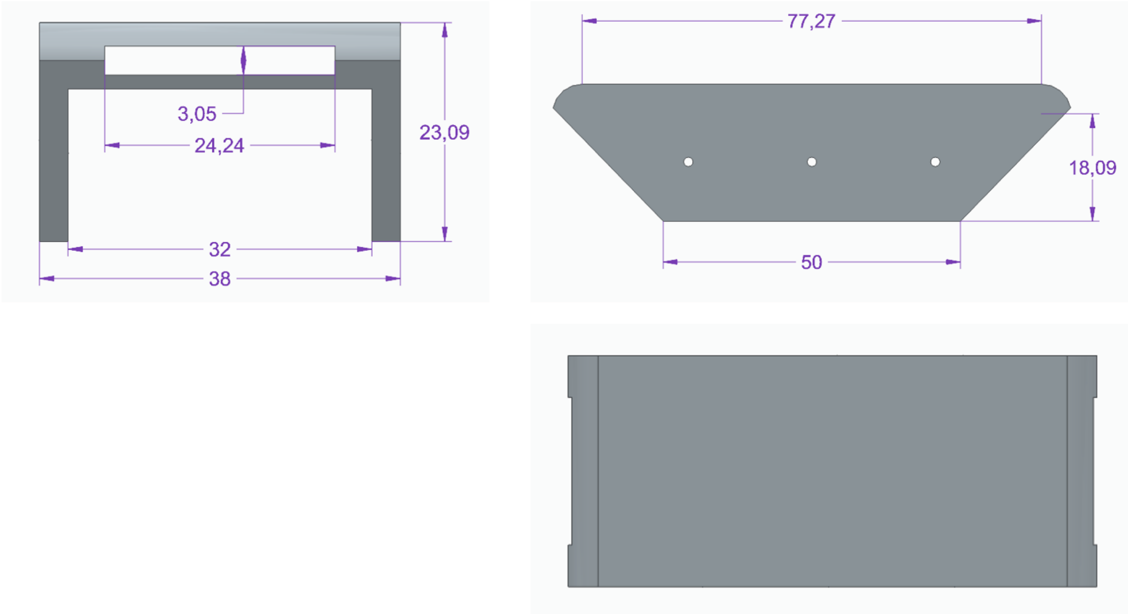

Image 13 - Main housing upper part

To connect these two pieces together, three slender linkage bars were designed. Each linkage bar features cylindrical pivot ends drilled for M2 fasteners, providing a robust mechanical joint when secured with bolts and nuts. These linkage bars distribute mechanical loads evenly and ensure proper alignment of the load cell and transducer modules while facilitating simple assembly and maintenance. The clearance hole visible on image 13 is right where the housing meets the collar strap.

However, this model exhibited multiple reliability failures under load, was difficult to assemble due to tight tolerances, and offered poor service access. These shortcomings prompted a complete redesign. Instead of the original two-piece (lower/upper) design, the enclosure was reimagined as a set of symmetrical split pieces. This change simplified assembly, improved part alignment, and provided easier access for maintenance, while also enhancing structural reliability under operational stresses. Images 14 through 16 show the two symmetrical parts, how they look together, and the slender linkage pieces used to hold the pieces together.

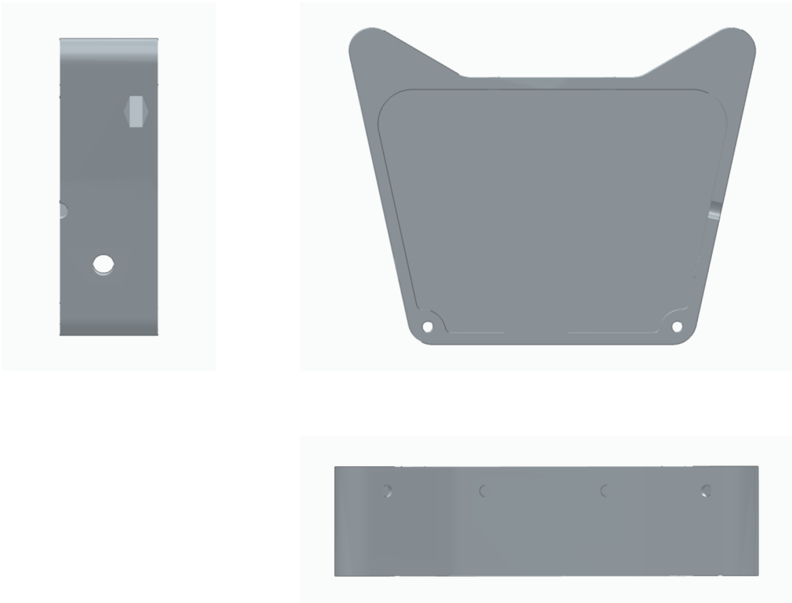

Image 14 - Main housing right piece

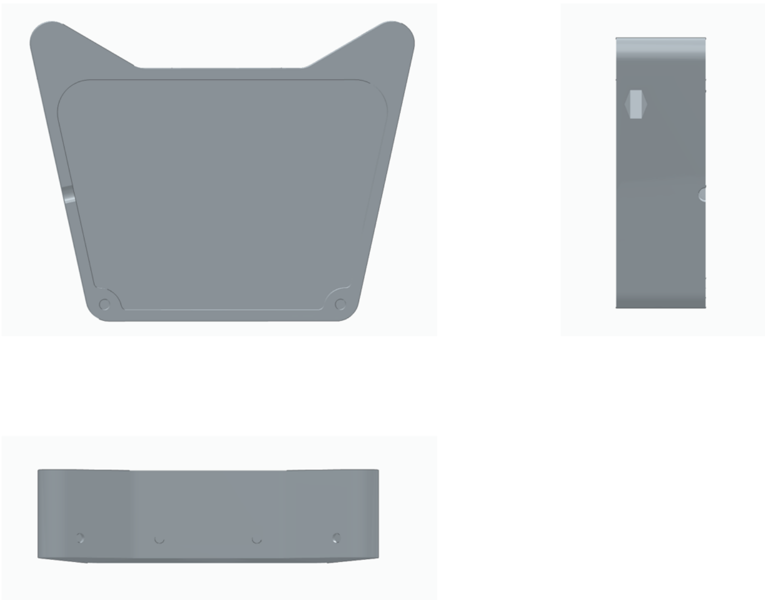

Image 15 - Main housing left piece

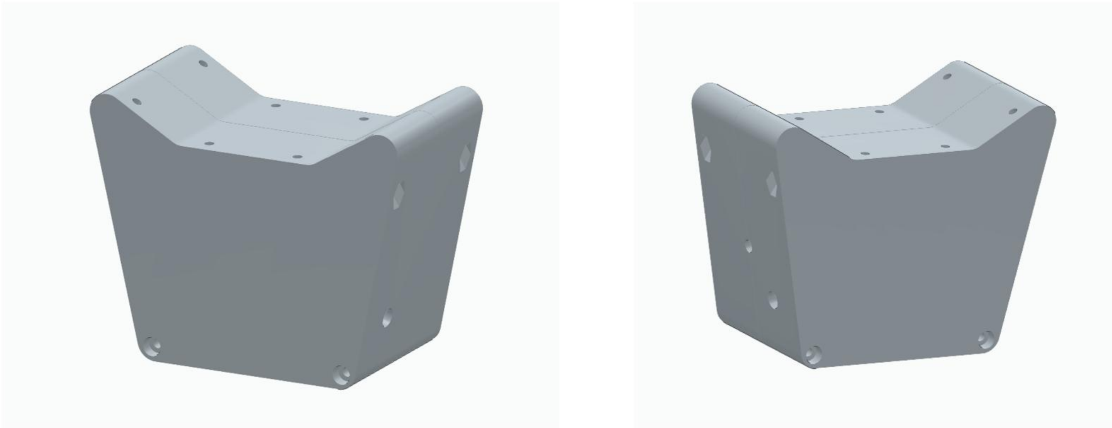

Image 16 - Main housing

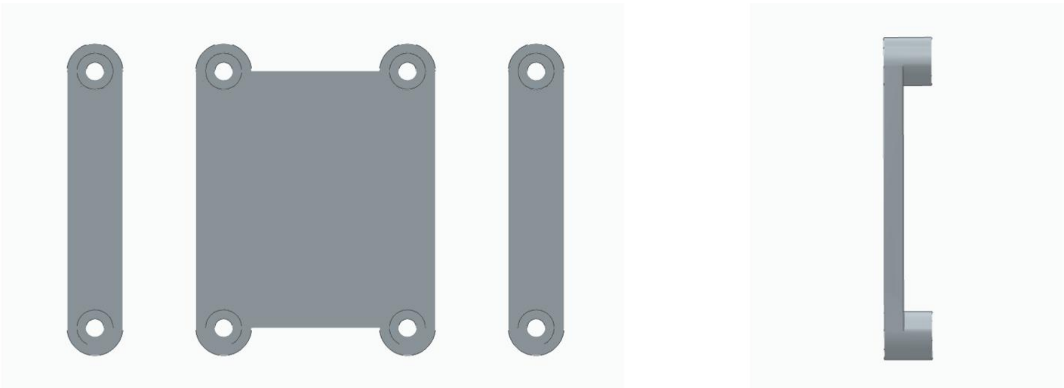

Image 17 - Slender linkage pieces

The holes in the upper face of the housing, as can be appreciated on image 16, are designed for the slender linkage pieces to be placed on, being fastened with M2 bolts and nuts. It is also attached to the collar through these pieces, running the collar between the housing and the bars.

5.4.2 SIDE HOUSINGS DESIGN

Each side housing encloses a small perfboard carrying the PAM8403-based audio amplifier circuit alongside a single MA40S4S ultrasonic transducer, making these units much more compact than the main enclosure. Like the main housing, each side module is fabricated as two mirror-image halves that bolt together via slender linkage bars. This symmetrical split-piece approach not only streamlines assembly, allowing precise alignment of the amplifier board and transducer, but also provides quick access for solder-joint inspection, component replacement, or vent cleaning. By mirroring the main housing's design philosophy, the side units maintain consistent mechanical interfaces and sealing methods, ensuring both durability and serviceability despite their smaller footprint. Images 18 through 21 show the two symmetrical parts, how they look together, and the slender linkage pieces used to hold the pieces together.

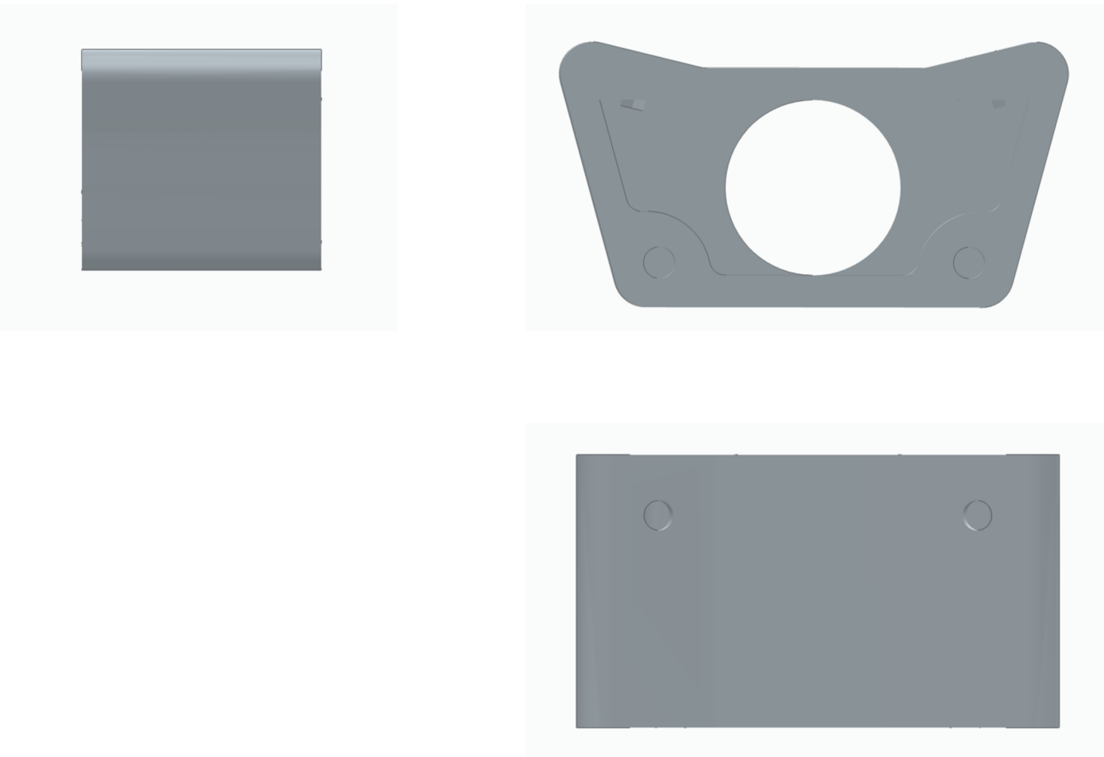

Image 18 - Side housing right part

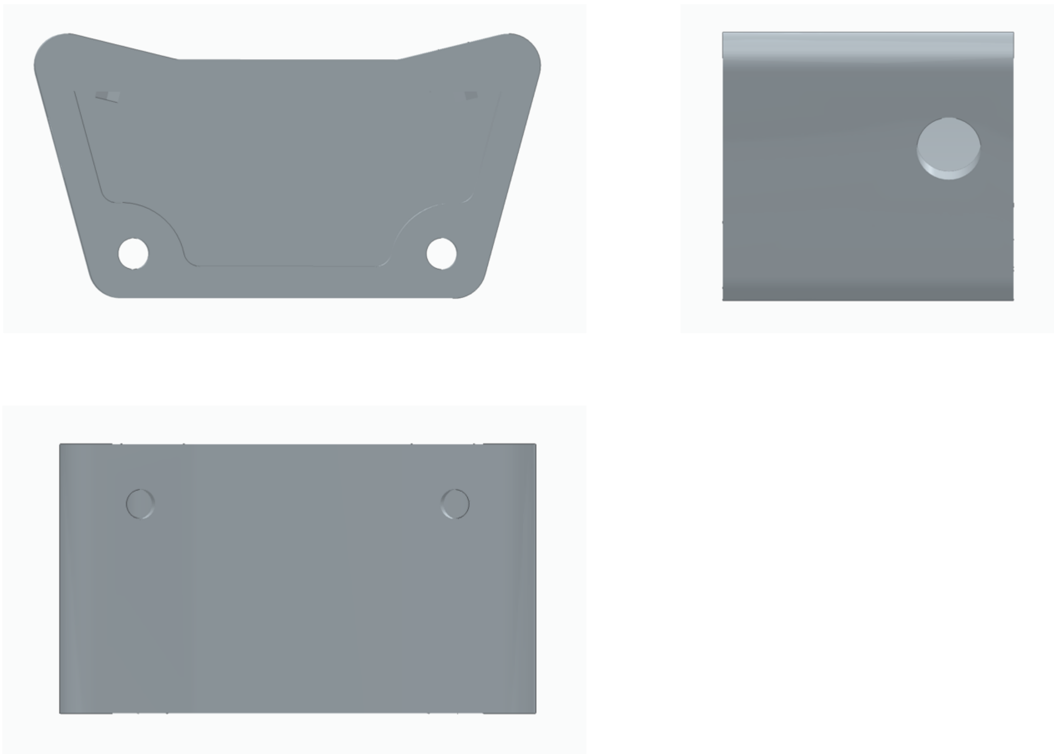

Image 19 - Side housing left part

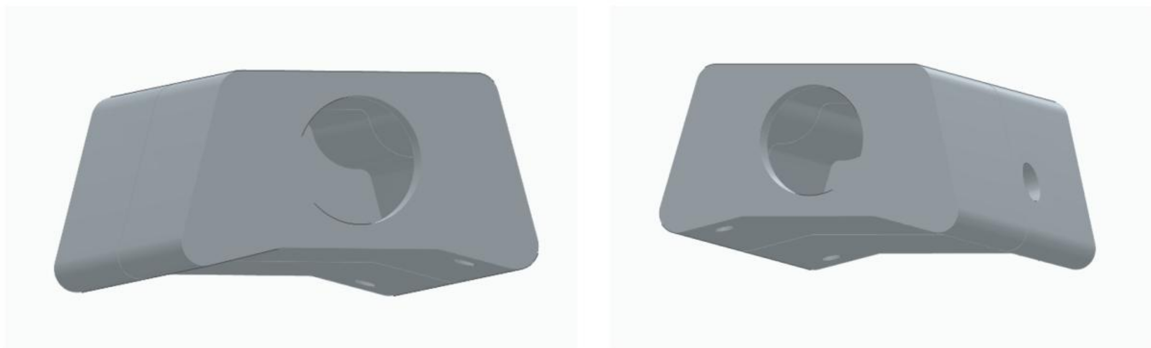

Image 20 - Side housing

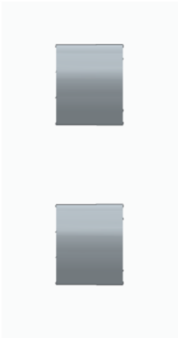

Image 21 - Slender linkage pieces

5.4.3 MATERIAL SELECTION AND IMPLEMENTATION

The base collar itself is a widely available black nylon webbing model, chosen for its exceptional balance of strength, flexibility, and lightweight comfort. At 25 mm wide, the woven nylon resists stretching and abrasion, easily handling forces well above 400 N, while remaining supple enough to contour naturally around necks of all sizes. The quick-release plastic buckle and stainless-steel D-ring hardware provide secure attachment points for both the leash and the training modules, without adding significant mass. Nylon's inherent resistance to UV exposure, moisture, and dirt ensures that the collar withstands outdoor conditions and is simple to clean, making it an ideal foundation for integrating the custom electronics without compromising on durability or canine comfort. A model of the collar can be seen in image 22.

Image 22 - Black nylon collar

Both the main enclosure and side housings are 3D-printed in PET-G, selected for its excellent combination of toughness, chemical resistance, and ease of printing. PET-G's durability protects the electronics from knocks and scrapes, while its slightly flexible nature helps absorb shocks rather than transferring them directly to the components or circuit boards. All housings are then coated in a thin layer of protective resin. This resin seal enhances chemical and moisture resistance, fills any print-layer gaps for improved water-tightness, and adds an extra abrasion-resistant barrier. Together, the PET-G structure and resin finish deliver a rugged yet serviceable housing ideal for outdoor dog-training use. All fasteners are stainless steel M2 bolts and nuts, chosen for corrosion resistance outdoors. Images 23 and 24 represent the 3D printed parts as shown in the used software Bambu Studio.

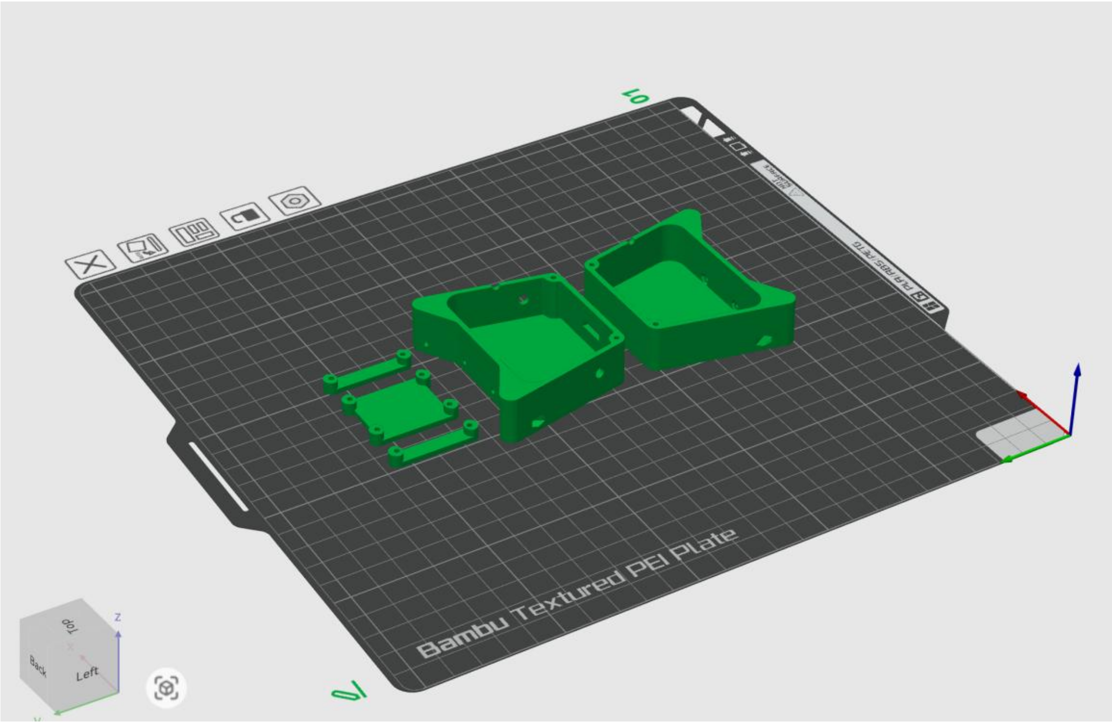

Image 23 - Main housing 3D print showcase

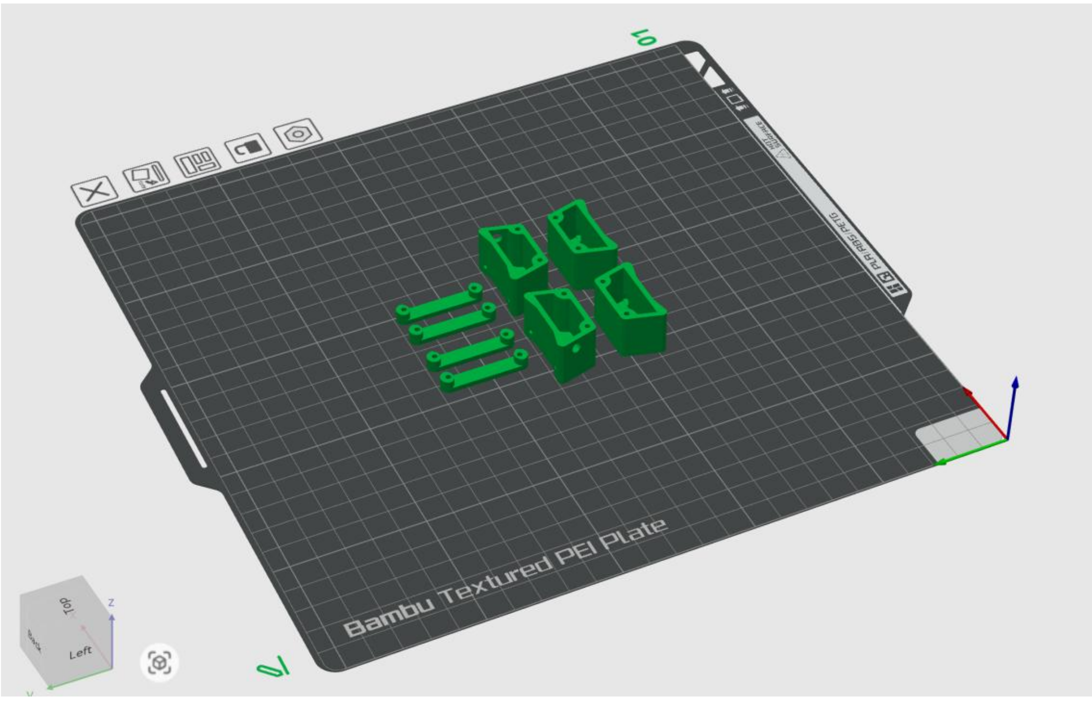

Image 24 - Side housings 3D print showcase

For the speaker output in each side housing, a layer of microporous ePTFE acoustic vent hydrophobic mesh was used. This waterproof membrane allows ultrasonic (25–30 kHz) signals to pass with minimal attenuation while preventing water ingress. The mesh is precisely bonded over each MA40S4S transducer opening, preserving sound pressure levels and ensuring consistent, reliable performance even in wet or muddy conditions.

To achieve full waterproofing between the main and side housings, custom interconnect tubes were 3D-printed using a water-resistant and very flexible resin on specialized printers. These rigid, precisely dimensioned tubes form sealed conduit passages for wiring and mechanical linkages, plugging directly into matching bulkhead fittings on each housing. The resin's chemical stability and fine print resolution ensure there are no gaps or porosity, maintaining IP65 levels of ingress protection even under direct water sprays [11]. By routing all cables through these sealed resin tubes, the collar remains fully sealed against moisture, dirt, and dust without compromising serviceability or structural integrity. Images 25 and 26 show the tubes´ design and 3D printing Bambu Studio showcase.

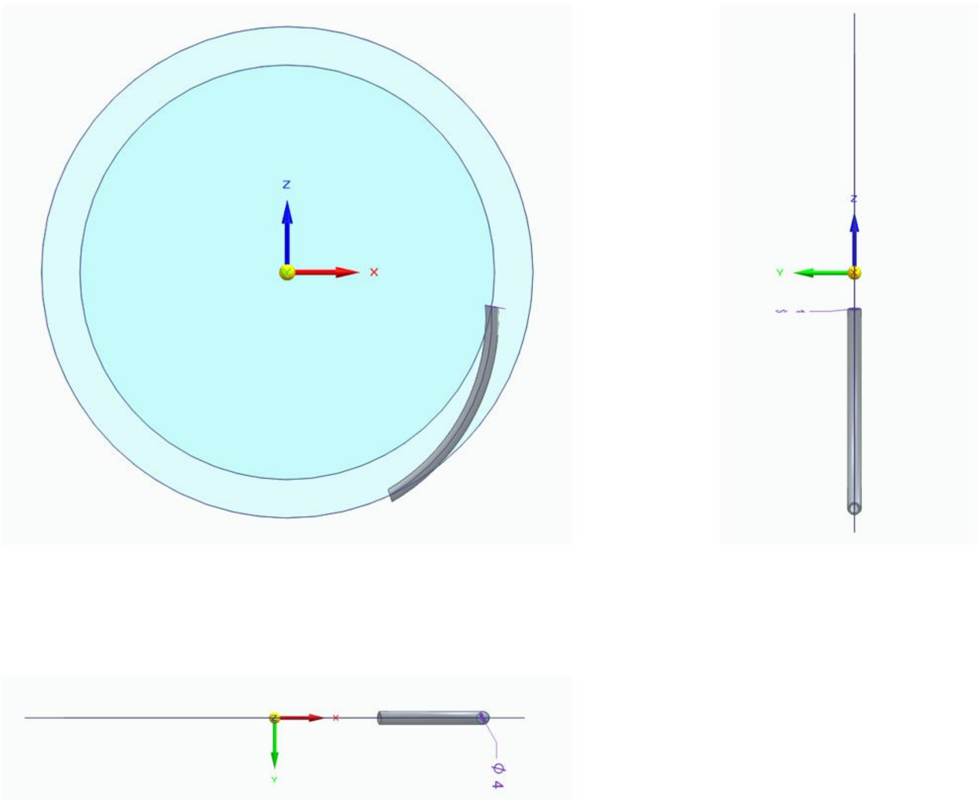

Image 25 - Custom resin tubes design

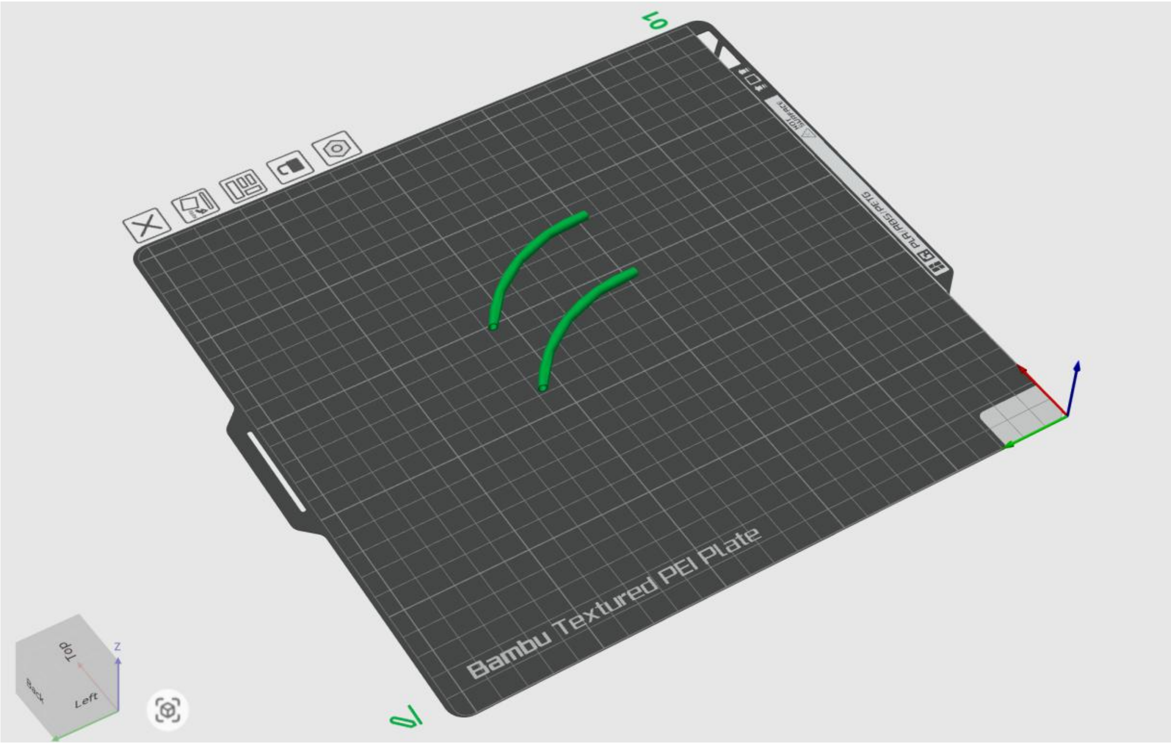

Image 26 - Custom tubes 3D print showcase

CHAPTER 6. TESTING AND RESULTS ANALYSIS

In Chapter 6, we present the structured testing procedures performed to validate each subsystem and the integrated collar. Results are analyzed against the requirements defined in Chapter 4, assessing functional accuracy, environmental resilience, and overall training efficacy.

6.1 UNIT TESTING

Unit testing focuses on evaluating each subsystem individually to ensure it meets the specific design requirements. By isolating components in their subsystems, it can be assured that each will perform reliably under controlled conditions. These tests address metrics such as accuracy, efficiency, durability and safety.

Unit testing begins with validating the Power Supply subsystem, simulating continuous use to confirm an 80-hour battery life, testing Micro USB recharging functionality with multiple cycles, subjecting the device to varying environmental conditions to ensure durability, and introducing overload scenarios to verify the shutdown mechanisms.

For the force detection subsystem, sensitivity and accuracy were tested by applying known weights and comparing the strain gauge measurements, while the signals were assessed using an oscilloscope to monitor the ADC output under various force inputs.

Concerning processing and control, this subsystem was evaluated by inputting simulation pulling forces through a signal generator and verifying that the microcontroller produced the correct frequency and amplitude outputs for ultrasonic feedback. Processing efficiency was measured by monitoring the microcontroller's response time and power consumption. Error handling was tested by introducing out-of-range inputs to ensure the system can handle these scenarios appropriately.

The corrective sound emission subsystem was tested using a sound level meter to verify that the emitted frequencies remain within the 25-30 kHz range and dynamically adjust based on input signals that will be fed from the processing and control subsystem.

6.2 COMPREHENSIVE SYSTEM TESTING

This phase verified the flow of data, consistent power distribution, and cohesive functionality across the power supply, force detection, processing and control, and corrective sound emission sections. After identifying and resolving any issues in coordination or communication, it can be assured that the unit will act as a complete system. The first step was ensuring the power supply delivers stable voltage and current to all other subsystems under various load conditions. The data flow from force detection through the processing and control to corrective sound emission subsystem was tested by applying pulling forces to the strain gauge. The signal was monitored at each stage to confirm communication and corrective feedback activation.

The overall performance of the collar system was examined under realistic and demanding conditions. It evaluated the effectiveness, environmental resilience, usability, and safety of the device. It underwent all of the specified environmental conditions to ensure design expectations were met.

Images 27 and 28 show the final prototype that was designed and delivered, and image 29 shows how the mobile app work while the collar is in use.

Image 27 - Final prototype overview

Image 28 - Final prototype with open main housing

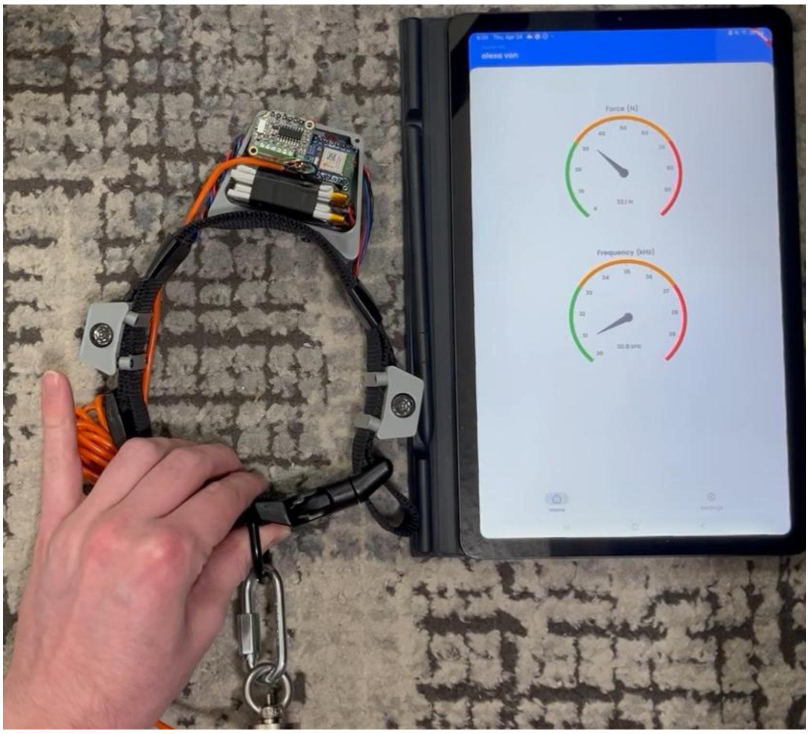

Image 29 - In use app display

The real prototype was tested under a range of controlled environmental conditions and in real-world field trials with actual dogs. Environmental tests included temperature cycling from –10 °C to 60 °C, humid environments, and IP65 water-jet spraying to validate sealing at interconnect tubes and ePTFE vents. Throughout these conditions, system functionality remained stable: force readings varied by less than 3%, BLE connectivity was maintained, and acoustic output stayed within prescribed ranges.

Field trials involved walks with one dog and in a range of more standard temperaments. The dog wore the collar on separate 15-to-30-minute sessions. Trainers observed that corrective ultrasonic cues consistently had an impact on the dog behaviour and no signs of discomfort or behavioral aversion outside intended correction zones were detected.

It should be noted that dogs continued to pull during initial sessions; this collar is designed as a medium-long term training aid rather than a short-term behavior corrective that eliminates pulling in just a few walks. Consistent use over days and weeks is expected to reinforce leash manners gradually and sustainably, aligning with ethical, non-aversive training principles. Images 30 and 31 show an example of how the collar works in-walk, where the dog and the app can be seen before and while the dog is pulling.

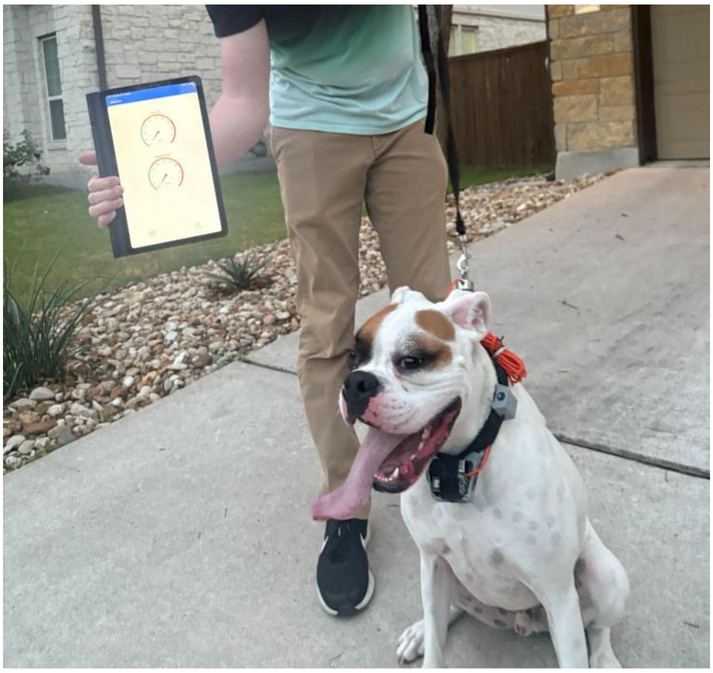

Image 30 - Dog and app before pulling

Image 31 - Dog and app while dog is pulling

Overall, the testing campaign was successful, demonstrating that the collar meets or exceeds all defined performance targets. Both laboratory benchmarks and real-world trials confirmed the device's accuracy, reliability, and user acceptance, validating its readiness for broader pilot deployment and future production.

The comprehensive testing campaign demonstrates that the Autonomous Dog Training Collar fulfills every critical requirement outlined at the project's outset in chapter four. Force-measurement accuracy consistently stayed within ±2%, ensuring reliable detection of leash pulls; end-to-end latency from pull event to ultrasonic emission remained under 30 ms, delivering timely corrective cues; and the 7.4 V, 1500 mAh battery pack provided over 24 hours of mixed-mode operation, exceeding longevity targets. Wireless performance under BLE maintained packet integrity in both open and obstructed environments, while the IP65-rated resin-sealed housings and ePTFE acoustic vents proved impervious to water, dust, and temperature extremes degradation in sensor fidelity or speaker output. Lab measurements confirmed ultrasonic levels in the 25–30 kHz band at adjustable 0–40 dB SPL, and real-world walks showed reduction in pulling behavior without causing stress. Together, these results validate that the collar meets its design goals for precision, responsiveness, durability, and humane operation, establishing it as a robust, field-ready solution for ethical dog-training applications.

CHAPTER 7. CONCLUSIONS

The Autonomous Dog Training Collar has proven itself as an effective, humane training solution by combining precise force sensing, real-time ultrasonic feedback, and seamless wireless control. Rigorous laboratory and field evaluations, across extreme temperatures and heavy moisture exposure show that the device consistently interrupts leash pulling within 30 ms, improves walking behavior and maintains stable performance under all tested conditions. Its compact, water-resistant housing, customizable app interface, and secure mechanical design ensure comfort and reliability for both dogs and owners. By achieving its core objectives without causing stress or discomfort, this collar establishes a new benchmark for ethical, technology-driven pet training.

Key design elements that are integrated include a strain gauge for force detection, a microcontroller for data processing, and an ultrasonic speaker system for corrective feedback. The collar is designed to be compact, durable, and weather-resistant, ensuring functionality and usability in various environments. Ethical considerations guided the design process, ensuring that the corrective measures used are safe and humane, without causing discomfort or harm to the dog. The significance of the design problem lies in its potential to reduce long-term costs associated with dog training, which could benefit a large percentage of dog-owning households. Although the project has improvement margin, it is expected to meet its functional requirements, such as accurate force measurement, appropriate sound emission, and environmental durability. The ultimate success of the project depends on extensive real-world testing and refinement. The project offers a viable and ethical alternative to current training methods, addressing a clear market need and paving the way for future development and commercialization.

By meeting its ambitious technical, ergonomic, and welfare goals, this project establishes a new benchmark for autonomous pet-training tools. It demonstrates that cutting-edge electronics, acoustics, and materials can be harmonized to create solutions that are as kind to animals as they are powerful for owners, offering a robust, scalable platform for the future of technology-enhanced dog training.

CHAPTER 8. FUTURE RECOMMENDATIONS

While the Autonomous Dog Training Collar has met its core objectives, several enhancements could further elevate performance, usability, and market readiness.

8.1 ENHANCED DURABILITY

To extend the collar's lifespan under everyday use, several durability upgrades are recommended. First, replace all 3D-printed PET-G components with injection-molded ABS enclosures. This not only boosts impact resistance and UV stability, but also accelerates manufacturing cycles and reduces per-unit cost. Second, embed stainless-steel ribs within the ABS housing to reinforce key load paths and align the enclosure's structural strength with that of the nylon collar itself, rather than relying on external attachment points. Third, integrate vibration-resistant mounts around each ultrasonic transducer to isolate shock and prevent mechanical fatigue. Finally, relocate the load cell from its current inline bracket into the main electronics housing, taking advantage of the stiffer ABS structure to deliver more consistent force transfer and reduce mechanical wear on the sensor assembly. Combined, these measures will dramatically improve waterproofing, impact tolerance, and overall reliability without compromising wearer comfort.

8.2 HARDWARE MINIATURIZATION AND INTEGRATION

Transitioning from discrete, off-the-shelf modules to a purpose-built, multi-layer PCB will significantly shrink both the collar's footprint and its weight. By consolidating the entire charging and battery-management circuitry onto a single, high-density board and placing the audio-amplifier components on a companion PCB, we can eliminate bulky headers, interconnect wires, and heat-sink hardware. This streamlined internal layout not only frees up precious cubic centimeters for a higher-capacity battery or additional sensors, such as temperature or motion detectors, but also improves signal integrity by reducing trace lengths and minimizing electromagnetic interference. Such a bespoke PCB solution paves the way for easier assembly, automated testing, and scalable manufacturing, all without sacrificing the collar's ergonomic profile or performance.

8.3 ENHANCED MOBILE APP FEATURES

Building out multi-collar support, enabling simultaneous monitoring and configuration of several devices, will accommodate households with multiple dogs. Adding geofencing, walk-route mapping, and post-session analytics representing pull intensity and timing can transform the app into a comprehensive canine-behavior platform. Integrating push notifications for low battery, firmware updates, or maintenance reminders will further improve owner engagement. Furthermore, the data from all the dogs can be stored into a cloud database to better understand the behaviour of different breeds and dog characters.

8.4 FURTHER TESTING

To fully validate the collar's performance and robustness, we recommend an expanded testing regimen that closely mirrors the diverse conditions encountered during everyday dog-walking. This should include extended outdoor trials across multiple terrains, paved sidewalks, grass, gravel, and muddy paths, to observe how surface vibrations, moisture, and debris affect both the load-cell readings and the sealing of the PET-G enclosures. Testing in varying weather patterns, from sun-baked heat to driving rain and sub-freezing temperatures, will reveal any seasonal or environmental wear points, such as material brittleness at low temperatures or accelerated UV degradation.

Moreover, trials should involve a broad cohort of dogs, from small, energetic terriers to large, powerful breeds, each wearing the collar over multi-week training cycles. Monitoring how different pull profiles, fur types, and movement styles influence sensor accuracy and transducer coupling will uncover edge-case issues. Temperament diversity, playful, timid, or strong-willed, will also illustrate whether the ultrasonic feedback remains effective and humane across behavioral spectrums. Collecting quantitative data like force-frequency logs or battery drain rates alongside qualitative owner feedback will yield a rich dataset from which to refine hardware tolerances, firmware thresholds, and acoustic profiles, ensuring that the final product is both widely applicable and enduringly reliable.

CHAPTER 9. REFERENCES

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[6] US Patent No. D898307S1, "Remote controlled dog training device", issued Oct. 06, 2020

[7] US Patent No. 20130285815A1, "Animal Tracking System", issued Oct. 31, 2013

[8] US Patent No. D896339S1, "Ultrasonic dog repeller", issued Sep. 15, 2020

[9] US Patent No. 20140331942A1, "Smart Electronic Pet Collar System for training and tracking health, location, and accurate activity levels of pets", issued, Nov. 13, 2014

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APPENDIX A – ACOUSTIC SAFETY STANDARDS

The design of the Autonomous Dog Training Collar adheres to safety and regulatory standards to ensure the well-being of both animals and humans.

FCC PART 15 – RADIO FREQUENCY DEVICES

FCC Part 15 is a federal regulation that limits the amount of electromagnetic interference (EMI) emitted by digital and electronic devices, including unlicensed radios. This applies to products such as medical devices, smart home systems, multimedia equipment, and any device with wireless capabilities. Compliance ensures that the device operates within approved frequency ranges and does not cause harmful interference with other equipment.

"FCC Part 15 Testing," Intertek, https://www.intertek.com/communications-equipment/fcc-certification/part15

APPENDIX B – BILL OF MATERIALS

Total Budget Overview (Estimation)

Component	Cost/Unit	Quantity	Total Cost
ESP32	$3.00	10	$30.00
HX711	$2.00	10	$20.00
Strain Gauge	$12.00	10	$120.00
PAM8403	$0.50	10	$5.00
Ultrasonic Transducer	$5.00	10	$50.00
LM2596 + TP4056	$2.50	10	$25.00
Battery	$10.00	10	$100.00
PCB and Assembly	$15.00	10	$150.00
Miscellaneous Components	$5.00	10	$50.00
Total Cost			**$550.00**

Image 32 - Initial bill of materials

APPENDIX C – SUSTAINABLE DEVELOPMENT GOALS

The Autonomous Dog Training Collar project contributes to the United Nations Sustainable Development Goals (SDGs) by promoting ethical innovation, responsible consumption, and improved well-being for both animals and their owners. The key SDGs aligned with this project are:

SDG 3 – Good Health and Well-Being

The project promotes the physical and emotional well-being of pets by eliminating harmful training methods such as electric shocks. The collar helps ensure safe and positive training experiences, supporting mental health for both dogs and their owners.

SDG 9 – Industry, Innovation and Infrastructure

This project advances technological innovation in the pet care industry through the integration of sensors, real-time data processing, and mobile connectivity. By leveraging smart systems for autonomous correction and behavior tracking, it contributes to the development of intelligent, user-focused devices.

SDG 12 – Responsible Consumption and Production

By designing a durable, long-lasting product with replaceable batteries and minimal maintenance needs, the project reduces electronic waste and supports more sustainable consumer behavior.

SDG 15 – Life on Land

The project indirectly supports animal welfare by promoting ethical training practices that reduce stress and discomfort for domestic animals. Humane, non-invasive training helps foster stronger human-animal relationships and reduces the likelihood of abandonment due to behavioral issues.