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# DESIGN, CONSTRUCTION AND PROGRAMMING OF A SOCIAL ROBOT FOR PERSONAL ASSISTANCE

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## Máster Universitario en Ingeniería Industrial

**Trabajo Fin de Máster**

# Design, Construction and Programming of a Social Robot for Personal Assistance


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**Madrid. September, 2024**

*"Art without engineering is dreaming,*
*engineering without art is calculating."*

Steven K. Roberts

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# Executive Summary

The evolution of robotics has significantly impacted a variety of industries, particularly in fields such as healthcare, education, and personal assistance, with **social robots** becoming increasingly integral. These robots are characterized by being able to understand and respond to human emotions and behaviors.

At the Center for Automation and Robotics (CAR), the Intelligent Control Group has made significant efforts to develop social robots for human-robot interaction and personal assistance. One example is Potato, a robot prototype that integrates an emotional model to achieve more natural and human-like interactions. Motivated by the successes and insights gained from the development of Potato and recognizing the growing demand for more advanced hardware, the next step was to design a new social robot.

This Master's Thesis focuses on the design, construction, and programming of a **new advanced social robot**, specifically tailored for **personal assistance** applications. The robot developed in this project is intended for use in scenarios such as **elderly care** and the management of **young diabetic patients**, to serve as a **supportive companion**. The robot's sophisticated human-robot interaction capabilities, including its ability to express **emotional responses**, were designed to meet the social and psychological needs of these vulnerable populations, thereby improving their quality of life.

The primary objective of this research was to create a **robust hardware platform** capable of facilitating advanced human-robot interactions, intended for use in future research projects that will involve programming different human-robot interaction software applications. The project sought to address the **limitations of existing models** and commercial solutions, which often lack customization, flexibility, and adequate privacy protections. The design, which was recognized in a competitive design contest, integrates superior interaction capabilities, aesthetic appeal, and powerful processing functions, ensuring that the robot can engage effectively and naturally with users in diverse personal and social contexts.

To achieve these goals, the project was organized into several key phases. Initially, a comprehensive review of the state-of-the-art in social robots for personal assistance was conducted to define the design requirements. Based on these insights, a **concept design** was developed, followed by **detailed mechanical, electrical, and electronic designs**. Components were carefully selected to align with the identified needs, and the robot's emotional expressions were designed based on the emotional model previously implemented in Potato.

The manufacturing process primarily utilized **3D printing** technology, which enabled the rapid prototyping and iteration of the robot's components. The assembly process involved integrating the mechanical, electrical, and electronic subsystems to create a **fully functional prototype**. This prototype was then submitted to several tests for validation purposes of its core functionalities.

**Figure R1.** Personal assistance robot prototype render.

Building upon this foundation, a **custom firmware was developed** focusing on creating a **modular architecture** to manage sensor data, control actuators, and facilitate communication between the robot's microcontroller and processing units. The firmware, implemented in C++, was designed to be extendable, allowing for **future** enhancements and the development of sophisticated **high-level applications**. Finally, a scope-restricted **demo** was developed to showcase the core capabilities of the robotic platform.

This thesis contributes to the field of social robotics by offering a detailed design of a **new social robot**, developing a **functional prototype**, creating an initial version of the robot's **firmware**, and **validating** the robot's **core functionalities**. The research not only advances the current state of social robotics but also lays a strong foundation for future studies aimed at further improving human-robot interaction.

**Keywords:** Social robotics, human-robot interaction, emotional intelligence, personal assistance, 3D printing, sensor integration and firmware development.

**UNESCO Codes:**

- 120304 Artificial Intelligence
- 120311 Computer software
- 330412 Control devices
- 330499 Robotics
- 630202 Social psychology

# Resumen Ejecutivo

La evolución de la robótica ha tenido un impacto significativo en una variedad de industrias, particularmente en campos como la salud, la educación y la asistencia personal, con los **robots sociales** volviéndose cada vez más integrales. Estos robots se caracterizan por su capacidad para entender y responder a las emociones y comportamientos humanos.

En el Centro de Automática y Robótica (CAR), el Grupo de Control Inteligente ha realizado esfuerzos significativos para desarrollar robots sociales para la interacción humano-robot y la asistencia personal. Un ejemplo de ello es Potato, un prototipo de robot que integra un modelo emocional para lograr interacciones más naturales y similares a las humanas. Motivados por los éxitos y aprendizajes obtenidos en el desarrollo de Potato, y reconociendo la creciente demanda de hardware más avanzado, el siguiente paso fue diseñar un nuevo robot social.

Este Trabajo Fin de Máster (TFM) se centra en el diseño, construcción y programación de un **nuevo robot social avanzado**, específicamente diseñado para aplicaciones de **asistencia personal**. El robot desarrollado en este proyecto está destinado a su uso en escenarios como el **cuidado de ancianos** y el acompañamiento de **pacientes jóvenes con diabetes**, sirviendo como un **compañero de apoyo**. Las sofisticadas capacidades de interacción humano-robot del robot, incluidas su habilidad de expresar **respuestas emocionales**, fueron diseñadas para satisfacer las necesidades sociales y psicológicas de estas poblaciones vulnerables, mejorando así su calidad de vida.

El objetivo principal de esta investigación fue crear una **plataforma de hardware robusta** que facilitara interacciones avanzadas humano-robot, con la intención de utilizarse en futuros proyectos de investigación que involucren la programación de diferentes aplicaciones de interacción humano-robot. El proyecto buscó abordar las **limitaciones de los modelos existentes** y de las soluciones comerciales, que a menudo carecen de personalización, flexibilidad y protección adecuada de la privacidad. El diseño, que fue reconocido en un concurso de diseño, integra capacidades de interacción superiores, atractivo estético y funciones de procesamiento potentes, asegurando que el robot pueda interactuar de manera efectiva y natural con los usuarios en diversos contextos personales y sociales.

Para alcanzar estos objetivos, el proyecto see organizó en varias fases clave. Inicialmente, se realizó una revisión exhaustiva del estado del arte de la robótica social y en particular para la asistencia personal con el fin de definir los requisitos de diseño. Basado en estos conocimientos, se desarrolló un **diseño conceptual**, seguido de **diseños mecánicos, eléctricos y electrónicos detallados**. Los componentes fueron seleccionados cuidadosamente para alinearse con las necesidades identificadas, y las expresiones emocionales del robot fueron diseñadas con la base del modelo emocional implementado previamente en Potato.

El proceso de fabricación utilizó principalmente la tecnología de **impresión 3D**, lo que permitió la creación rápida de prototipos y la iteración de los componentes del robot. El proceso de ensamblaje involucró la integración de los subsistemas mecánicos, eléctricos y electrónicos para crear un **prototipo completamente funcional**. Este prototipo se sometió a diversas pruebas para validar sus funcionalidades principales.

**Figure R1.** Render del prototipo de robot de asistencia personal.

Sobre esta base, se desarrolló un **fimware personalizado** enfocado en crear una **arquitectura modular** para gestionar los datos de los sensores, controlar los actuadores y facilitar la comunicación entre la unidad de procesamiento y el microcontrolador del robot. El firmware, implementado en C++, fue diseñado para ser extensible, permitiendo futuras mejoras y el desarrollo de aplicaciones avanzadas de alto nivel. Finalmente, se desarrolló una **demostración** con un alcance restringido para mostrar las capacidades principales de la plataforma robótica.

Este TFM contribuye al campo de la robótica social ofreciendo un diseño detallado de un **nuevo robot social**, desarrollando un **prototipo funcional**, creando una versión inicial del **firmware** del robot, y **validando** sus **funcionalidades principales**. La investigación no solo avanza el estado actual de la robótica social, si no que también sienta una base sólida para futuros estudios dirigidos a mejorar aún más la interacción humano-robot.

**Keywords:** Robótica social, interacción humano-robot, inteligencia emocional, asistencia personal, impresión 3D, integración de sensores y desarrollo de firmware.

**Códigos UNESCO:**

- 120304 Inteligencia Artificial
- 120311 Software
- 330412 Dispositivos de control
- 330499 Robótica
- 630202 Psicología social

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# List of Acronyms

**ABS** Acrylonitrile Butadiene Styrene. xxi, 16, 70, 74

**AI** Artificial Intelligence. 1, 3, 9, 62, 138

**AMQP** Advanced Message Queuing Protocol. 33, 82

**CAD** Computer-Aided Design. 23, 24

**CAR** Center for Automation and Robotics. xix, 1, 7, 13, 20, 36, 38, 78

**CNC** Computer Numerical Control. 26

**CPU** Central Processing Unit. 57, 62

**CSIC** Spanish National Research Council. 1, 7, 13, 38

**DOF** Degrees Of Freedom. xx, xxi, 38, 39, 43–45, 57, 71

**DXF** Drawing Exchange Format. 24

**FACS** Facial Action Coding System. 14

**GPIO** General-Purpose Input/Output. 29, 30, 55, 56, 64, 76

**GPU** Graphics Processing Unit. 62

**HRI** Human Robot Interface. xx, 10, 12, 37, 83

**I2C** Inter-Integrated Circuit. 29, 56, 57, 59, 60, 64, 76, 97

**ICSR** International Conference on Social Robotics. 9

**IDE** Integrated Development Environment. 29, 30

**IMU** Inertial Measurement Unit. xxi, 56, 57, 107

**LCD** Liquid Crystal Display. xx, xxii, 14, 25, 38, 47, 52, 54, 55, 63, 64, 74, 98–102

**LDR** Light Dependent Resistor. xxi, 36, 38, 48, 56, 89, 97, 99–101, 103, 108

**LED** Light Emitting Diode. xvii, xx, xxii, 28, 29, 38, 42, 43, 46, 47, 52, 54–56, 65, 70, 74, 75, 77, 83, 89, 94, 95, 98–102, 108

**MBDD** Mental, Behavioral, and Developmental Disorder. 18

**ML** Machine Learning. 9

**MOSFET** Metal-Oxide Semiconductor Field-Effect Transistor. 55, 56

**NFC** Near Field Communication. xx, xxi, 50, 51, 59, 63, 107

**NLP** Natural Language Processing. 8, 10, 62, 137

**OOP** Object Oriented Programming. 31

**PCB** Printed Circuit Board. 61, 63, 65, 108

**PETG** Polyethylene Terephthalate Glycol. xxi, 16, 69, 70, 72, 73, 76, 94, 138

**PLA** Polylactic Acid. 16, 69, 73

**PVC** Polyvinyl Chloride. xxi, 47, 70, 74

**ROS** Robot Operating System. 32, 82, 92

**RTC** Real-Time Clock. xxi, 60, 89

**SCL** Serial Clock Line. 29, 64, 75

**SDA** Serial Data Line. 29, 64, 76

**SDG** Sustainable Development Goal. xxii, 5, 138, 139

**SPM** Spherical Parallel Manipulator. xvii, xx, xxi, 43, 44, 71, 73, 74

**SSD** Solid State Disk. 36, 62, 63, 77

**STL** Standard Triangle Language. 26

**TLS** Transport Layer Security. 33

**TPU** Thermoplastic Polyurethane. 16

**TTL** Transisitor-Transistor Logic. 61

**UART** Universal Asynchronous Receiver-Transmitter. 29, 61, 62, 64

**UML** Unified Modeling Language. xxii, 86

**UPM** Technical University of Madrid. 1, 7, 13, 23, 24, 38

**URDF** Unified Robot Description Format. 24, 108

**USB** Universal Serial Bus. 27, 29, 43, 61, 63, 77

**VPN** Virtual Private Network. 27

**WBS** Work Breakdown Structure. xviii, xxii, 141, 142

Chapter 1

# Introduction

The present chapter introduces the developed work, providing a brief contextualization of the project and its motivation. It outlines the work objectives, highlights the main contributions, and describes the structure of this document.

## 1.1. Background

The field of **robotics** has advanced significantly since the introduction of robots into industrial settings during the third industrial revolution. Industry 4.0 has further propelled robots beyond factory floors, enabling them to work collaboratively with humans in diverse environments. Robots are now integral to applications in agriculture, healthcare, surveillance, and personal assistance.

One of the most promising and rapidly developing areas within robotics is the design and deployment of **social robots**. Social robots are engineered to interact seamlessly with humans, providing support, companionship, and assistance in daily activities. These robots are equipped with advanced sensors, Artificial Intelligence (AI), and communication technologies, allowing them to understand and respond to human emotions and behaviors. Initially, social robots performed basic tasks with limited interaction, but advancements in **AI** and **affective computing** have greatly expanded their capabilities. Today, they can manage a range of activities from medication reminders to engaging in meaningful conversations.

At the Center for Automation and Robotics (CAR), a joint center of the Technical University of Madrid (UPM) and the Spanish National Research Council (CSIC), the Intelligent Control Group has made significant efforts to develop social robots for human-robot interaction and **personal assistance**. Over the past decade, they have successfully developed three notable social robots: Urbano [1], Doris [2], and Potato [3]. These robots have been applied in various scenarios, including serving as **tour guides** and **providing companionship** to isolated older adults and young adolescent diabetic patients.

The Potato robot project, which can be seen in Figure 1.1, highlights the integration of emotional models into social robotics to achieve **more natural and human-like interactions**. Supervised by psychologists, the emotional model implemented on Potato is based on social psychology and allows engineers to adapt the robot's personality and lets psychologists define input-output relationships without technical knowledge. The successful validation of this model through experiments demonstrated the effectiveness of emotional responses in enhancing human-robot interaction.

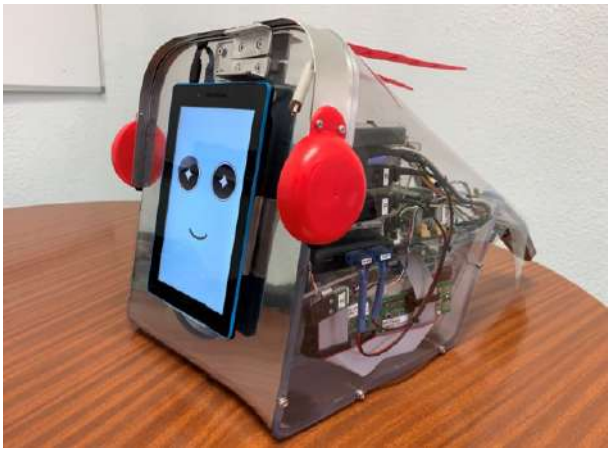


**Figure 1.1.** Potato personal assistance robot [3].

## 1.2. Motivation

Motivated by the successes and insights gained from the development of Potato and recognizing the growing demand for more advanced personal assistance, the next step was to design a new social robot. This new robot aims to incorporate **improved interaction opportunities**, more **powerful processing** capabilities, a more **aesthetic design**, and **enhanced functionality** to interact more naturally and effectively with users in various personal and social contexts.

The decision to create a new robot rather than relying on existing **external solutions**, stems from several critical motivations. Mainly, existing solutions often **lack the customization and adaptability** needed to meet specific research and application requirements, and have **insufficient intelligence capabilities**, working mostly as finite-state machines, or a very **high cost**. Developing a new robot in-house additionally offers complete control over **data handling and privacy**, ensuring that sensitive information is managed according to specific ethical guidelines and regulatory requirements by running the AI models locally. This approach is particularly important given the growing concerns about privacy in social robotics, as highlighted by Lutz and Tamò-Larrieux [4], who found that privacy concerns significantly affect users' intentions to use social robots.

The hardware design for the robot presented in this Master's Thesis was the **winner of a design competition** held for students from the *Escuela Técnica Superior de Ingenieros Industriales* and the *Escuela Técnica Superior de Ingeniería y Diseño Industrial*. The winning design, chosen for its feasibility, aesthetic appeal, and innovative features, served as the foundation for this advanced social robot. This new robot is expected to significantly enhance the ability to explore and implement sophisticated human-robot interaction scenarios, ultimately contributing to the advancement of social robotics research and applications.

## 1.3. Objectives

### 1.3.1. Main Objective

The primary objective of this Master's Thesis is to **develop the hardware platform for a sophisticated social robot** capable of advanced human-robot interaction and emotional response for personal assistance. The project seeks to overcome shortcomings of earlier models and commercial alternatives by ensuring greater customization, flexibility, and enhanced data privacy, with improved features to deliver effective personal assistance and engagement.

### 1.3.2. Specific Objectives

In order to accomplish this main objective the project has been divided into the following secondary objectives, which can be used as control milestones:

- Study the design of state-of-the-art robots for personal assistance and determine the design requirements.
- Create the concept design of the social robot based on the identified design requirements.
- Develop detailed mechanical, electrical, and electronic designs for the social robot and select appropriate hardware components.
- Design and develop emotional faces and transitions to enhance human-robot interaction.

- Develop testing prototypes, select optimal materials, and manufacture and assemble the robot components. Integrate the different subsystems and conduct iterative testing and improvements.

- Design and develop an initial version of the robot firmware for hardware validation purposes that integrates with the robot software architecture.

- Test and validate the robot subsystems and the overall system through a comprehensive demo.

## 1.4. Work Contributions

The completion of these objectives has involved significant technical and research achievements. The main contributions of this work are:

- **Detailed design of a new social robot for personal assistance:** Following a conceptual design phase that analyzed different alternatives, a mechanical 3D model of the robot was developed, along with the electrical and electronic design. Additionally, the emotional expressions corresponding to the emotional model of Potato were designed and developed for the new robot. The selection of hardware components ensured that the robot met the identified requirements, thereby overcoming the limitations of previous models and commercial solutions.

- **Manufacturing of the designed robot:** Based on the robot design, a fully functional prototype was built primarily through 3D printing, although other methods were also used. After manufacturing the individual robot pieces, the mechanical parts were assembled and integrated with the electrical and electronic subsystems.

- **Firmware development:** An initial version of the firmware for the robot was developed based on a node hierarchical architecture. The firmware, written in C++, integrates sensor data, manages actuator control, and handles communication between the microcontroller and the processing units of the robot. This integrates with the modular software architecture inspired on Potato's, enabling the development of high-level applications.

- **Prototype Testing and Validation:** The main elements of the robot were tested individually, and the entire system was validated through a comprehensive demo. This showcased the robot's potential to enhance human-robot interaction through emotional engagement by demonstrating its core capabilities.

## 1.5. Structure of the Document

The document is structured into eight chapters, each addressing a different aspect of the project, and three appendixes including additional documentation.

- **Chapter 1 – Introduction:** Introduces the developed work, contextualizing the project and describing its motivation. It presents the work objectives, the main contributions and the document structure.
- **Chapter 2 – Literature Review:** Discusses the current state of social robotics, covering definitions, characteristics, historical development, design principles, key technologies, applications, and case studies. It also addresses the challenges and future directions in the field.
- **Chapter 3 – Methodology:** Outlines the tools and methods used, including design, hardware, firmware, and software tools.
- **Chapter 4 – Robot Design:** Details the design process, including the design goals, concept design, mechanical design, and electrical and electronic design. It also covers the design of the robot's emotional faces.
- **Chapter 5 – Robot Manufacturing:** Describes the manufacturing process, materials and components, techniques, assembly, and modifications made to the initial design.
- **Chapter 6 – System Architecture and Firmware Development:** Presents the overall system architecture and the firmware development process, explaining its designed architecture, its core functionalities and its integration with the software.
- **Chapter 7 – Results and Discussion:** Provides an overview of the results, testing and validation, observations and insights, and a description of the demo prepared with the robot.
- **Chapter 8 – Conclusions and Future Work:** Summarizes the main conclusions and suggests directions for future work.

The appendixes include the main assembly technical drawings, the study of economic, social, legal, and environmental impacts and contribution to Sustainable Development Goals (SDGs), and the temporal planning and budget of the project.

Chapter 2

# Literature Review

This chapter provides a comprehensive review of the literature on social robotics. It begins by defining social robots and their core capabilities and then categorizes social robots and explores their historical development and future challenges. Following this, it delves into the design principles and technologies that distinguish social robots and examines various applications of social robots in personal assistance, education, healthcare, and entertainment. Finally, it highlights specific social robots developed at CAR (UPM-CSIC).

## 2.1. Background on Social Robotics

Social robots can be understood as robots with **social interaction capabilities** [5] that generate social **responses in users** [6] and adhere to the **social rules** associated with these interactions [7]. These robots are designed to communicate with humans in ways that feel natural and intuitive, both verbally and non-verbally [8], exhibiting behaviors that allow them to operate autonomously, engage in social interactions, and display emotional responses [9]. Though different definitions exist [10], in general they all include the following concepts:

- **Autonomy:** Social robots are expected to operate independently, making decisions and performing tasks without constant human intervention [11].
- **Interaction capabilities:** The ability to interact with humans through multiple modalities (e.g., speech, gestures, facial expressions) is essential for social robots. These interaction capabilities are fundamental for engaging with users in a natural and intuitive manner [5].

- **Empathy generation:** Generating empathy involves recognizing and responding to human emotions, which is key for social robots to build a rapport with users. This capability enhances user engagement and can provide emotional support [11].
- **Adherence to social norms:** Social robots need to operate within established social and cultural norms to be accepted and effective in human environments. This ensures their actions are appropriate and well-received [12].
- **Communication skills:** Effective communication is a cornerstone of social robotics, enabling robots to convey and understand messages through Natural Language Processing (NLP) and non-verbal cues. This enhances the interaction quality and user experience [13].

### 2.1.1. Classification of Social Robots

In [5], Breazeal categorizes social robots in ascending order of interaction complexity and the depth of social cognition required:

1. **Socially evocative:** These robots leverage humans' tendency to anthropomorphize by eliciting emotional responses through nurturing or creative engagement.
2. **Social interface:** Utilizing human-like social cues and communication methods, these robots provide intuitive interfaces but have shallow social cognition models.
3. **Socially receptive:** Passive in interactions, these robots benefit from learning through imitation, requiring more sophisticated human social competency models.
4. **Sociable:** Actively engaging with humans to meet internal social needs, these robots possess advanced social cognition for complex and meaningful interactions.

### 2.1.2. Historical Development and Future Challenges

The field of social robotics has evolved significantly since its inception, driven by advancements in technology and an increasing interest in enhancing human-robot interactions. The journey began with early **biologically inspired robots**, such as Walter's tortoises in the late 1940s [14], which demonstrated rudimentary social behaviors through simple phototaxis mechanisms[1]. These early experiments paved the way for the development of more complex systems that incorporated principles of stigmergy[2] and collective behavior observed in social insect societies. Researchers like Deneubourg pioneered the application of these principles in the early 1990s to create robot collectives capable of performing tasks through indirect communication and self-organization [15].

[1] Phototaxis refers to the movement of an organism or robot in response to light.
[2] Stigmergy is a mechanism of indirect coordination through the environment between agents or actions.

As the field progressed, the focus shifted towards individualized social robots, capable of recognizing and interacting with humans on a personal level. This transition was marked by the development of robots that could perceive and respond to human emotions, a capability that was crucial for creating meaningful interactions. A notable advancement in the field was the introduction of robots such as Kismet [5], which can be seen in Figure 2.1, and Cog [16] at the MIT Media Lab in the late 1990s and early 2000s. Designed by Cynthia Breazeal, **Kismet**, widely regarded as the first social robot, could engage in expressive face-to-face interactions using vocalizations and facial expressions to communicate emotions, demonstrating the potential for robots to interact naturally with humans.

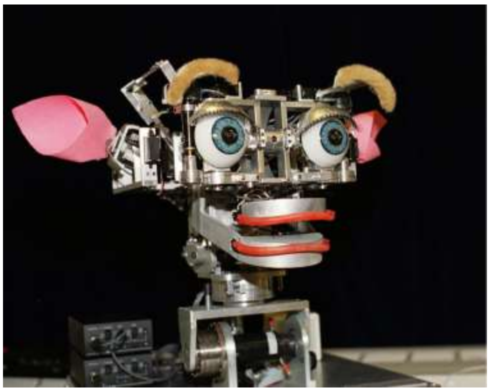


**Figure 2.1.** Kismet robot [5].

In the early 2000s, commercial and research applications of social robots expanded significantly. Robots like Sony's AIBO [17], a robotic pet dog, and Paro [18], a therapeutic seal robot, were developed to provide companionship and emotional support, particularly for the elderly. These developments showcased the practical benefit of social robots in everyday life.

Recent advancements in AI, Machine Learning (ML), and sensor technologies have further enhanced the capabilities of social robots. Modern robots such as Pepper by Softbank Robotics [19] and NAO by Aldebaran Robotics [20] are now used in diverse settings, including **education, healthcare, and customer service**. Current research topics in social robotics have diversified considerably. For instance, at the 15$^{th}$ International Conference on Social Robotics (ICSR) held in 2023 [21], key topics included human-robot collaboration, the impact of robots on engagement during teaching interactions and learning outcomes, as well as the ethical, legal, and social requirements for assistance robots in healthcare.

Future research in social robotics will need to address the **significant challenges** currently facing the field while continuing to push the boundaries of what robots can achieve. **Ethical and data privacy concerns** are paramount, especially in healthcare and personal assistance scenarios where sensitive information is handled. Ensuring that robots operate within ethical guidelines and respect user privacy is crucial for gaining **public trust and acceptance** [9]. Researchers such as Korn [22] and Shaw-Garlock [23] have discussed the ethical and societal implications of social robots, calling for a balanced approach that considers both technological advancements and human factors. Furthermore, **enhancing the emotional intelligence** of robots is essential for enabling them to respond swiftly and appropriately in dynamic environments. Additionally, the development of **standardized metrics for evaluating human-robot interaction**, as proposed by Bartneck et al. [24] and Heerink et al. [25], is crucial to advancing the field and ensuring the effective deployment of social robots across various domains.

## 2.2. Design Principles and Technologies

After establishing a general background on social robots, it is essential to delve into the specific design principles and technologies that set social robots apart from conventional ones. Understanding these principles, morphological considerations, emotional behavior, and manufacturing materials and techniques, is crucial for appreciating their unique capabilities and functionalities.

### 2.2.1. General Design Principles

Social robots are designed to interact with humans in various settings, including domestic, educational, and healthcare environments. Several key design principles ensure these interactions are intuitive, engaging, and beneficial [11][26]:

- **User-centered interaction:** It involves designing robots that understand and respond to human language and actions seamlessly. In social robots the concept of Human Robot Interface (HRI) is crucial. It is defined as the medium through which humans and robots interact. This includes the use of NLP to make communication effortless, as well as gesture and facial recognition to interpret and replicate human expressions. Context awareness further enhances this interaction by allowing robots to understand and respond appropriately to the situation at hand.
- **Emotional and social intelligence:** It is crucial for building rapport and trust with users. Affective computing integrates sensors and algorithms to detect and respond to human emotions [27]. Behavioral modeling ensures robots exhibit socially acceptable behaviors, and adaptive learning enables them to improve their responses over time, making interactions more natural and effective.
- **Real-time responsiveness:** It is essential for maintaining engagement in human-robot interactions. This principle requires robust perceptual, processing and actu-

ation systems that allow robots to operate in real-time, responding promptly and appropriately to dynamic interactions. Temporal synchrony ensures that the robot's responses are well-timed, maintaining the natural flow of conversation.

- **Motivation and behavior regulation:** It is key for proactive and balanced interactions. Self-motivated interaction drives robots to engage with their environment and human counterparts based on internal goals. Behavioral regulation allows robots to adjust their interactions based on feedback, ensuring that they are neither overwhelming nor under-stimulating the user.
- **Expressive communication:** It involves the use of clear social signals, such as facial expressions, body posture, and vocalizations, to convey the robot's internal states. This principle helps both robots and humans adjust their behaviors to each other, enhancing mutual understanding and the quality of interaction.
- **Continuous improvement and personalization:** It is critical for refining and enhancing user experience over time. User feedback and regular evaluation of robot performance is essential for this process and allows more meaningful and effective interactions.

### 2.2.2. Morphological Considerations

The physical design of social robots significantly impacts their effectiveness and acceptance. Key morphological considerations include aesthetic appeal, ergonomic design, and safety features.

#### 2.2.2.1. Aesthetic Appeal

Ensuring that robots have a pleasing and non-threatening appearance is crucial for user acceptance [26]. Incorporating human-like features such as eyes, mouth, and limbs enhances the robot's ability to express emotions and engage users. A friendly and relatable appearance encourages users to interact more naturally with the robot. However, it is important to consider the **"Uncanny Valley"** phenomenon [28], introduced by Masahiro Mori in 1970, where robots that appear almost human but not quite perfect can cause discomfort or repulsion. Figure 2.2 shows a graph of the affinity versus the human likeness. An example of robot that lies in this valley is Geminoid HI [29], from Hiroshi Ishiguro Laboratories, which is shown in Figure 2.3. Caricatured representations, which are less realistic but more approachable, may be more effective in avoiding this issue.

#### 2.2.2.2. Ergonomic Design

Creating robots with dimensions and shapes appropriate for their intended environment and user group is essential [30]. For example, robots designed for children may

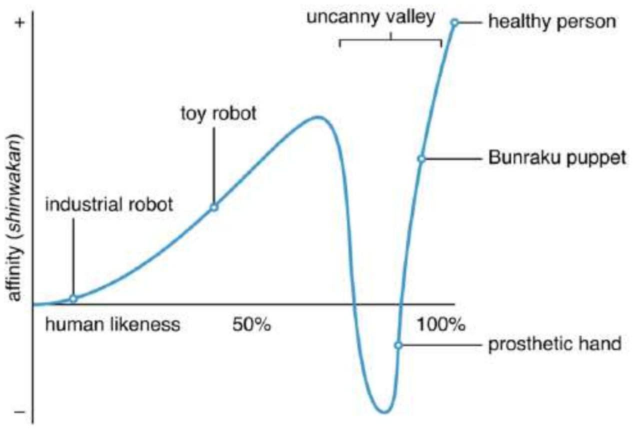



**Figure 2.2.** "Uncanny Valley" curve [28].

**Figure 2.3.** Geminoid HI [29].

be smaller and more playful. Ensuring smooth, natural movements helps robots avoid appearing mechanical, enhancing usability and comfort for users.

#### 2.2.2.3. Safety Features

Safety is a critical aspect of robot design to prevent accidents and ensure user trust [31]. Robots should be constructed from materials that minimize injury risk, such as soft materials and rounded edges. Stability and balance are also crucial to prevent falls and collisions.

### 2.2.3. Emotional Behavior

Emotions play a significant role in human behavior, communication, and interaction. Emotions are complex phenomena often tightly coupled to social context. Moreover, much of emotion is physiological and depends on embodiment. In recent years, emotion has increasingly been used in HRI design, primarily because of the recognition that people tend to treat computers as they treat other people. Moreover, many studies have been performed to integrate emotions into products, including electronic games, toys, and software agents [32]. This integration is a core aspect of affective computing, a field introduced by Rosalind Picard in 1997 [27], which focuses on developing systems that can recognize, interpret, and simulate human emotions.

#### 2.2.3.1. Artificial Emotions

The primary purpose of artificial emotions in social robots is to enhance believable human-robot interaction. They provide feedback on the robot's internal state or goals and act as a control mechanism, driving behavior and reflecting adaptations over time. These emotions are generated through complex algorithms, forming an emotional model that uses various inputs and contexts. Common algorithms include neural networks, fuzzy logic, Markov models, probability tables, and reinforcement learning [3]. Understanding emotional models in robotics requires delving into psychological theories of emotion:

- **Basic discrete categorization:** This theory classifies emotions into a finite set of basic emotions, each associated with distinct mental states and expressions [33]. For instance, Ekman and Friesen's classification includes surprise, happiness, fear, sadness, disgust, anger, and neutral [34].
- **Valence-intensity categorization:** Emotions are described along dimensions of valence (positive to negative) and intensity (high to low), offering a continuous spectrum of emotional states [35].
- **Color categorization:** This model uses segments and colors to represent emotions, with intensity indicated by proximity to the center of a color wheel. One relevant theory is **Plutchik's classification**, which initially proposed eight emotions [36].

There is no consensus on how many emotions a robot should have, as it depends on the application. For instance, the **Potato** robot developed by the Intelligent Control Group at CAR (UPM-CSIC) employs a color categorization emotional model based on Plutchik's with six dimensions (**twelve emotions**) [37], such as happiness-sadness and fear-calm, which are modulated continuously based on stimuli using fuzzy logic. A representation of this dimensional emotional model can be seen in Figure 2.4. Simulated emotions are typically defined by facial expressions, body language, gestures, and the tone, cadence, and use of words.

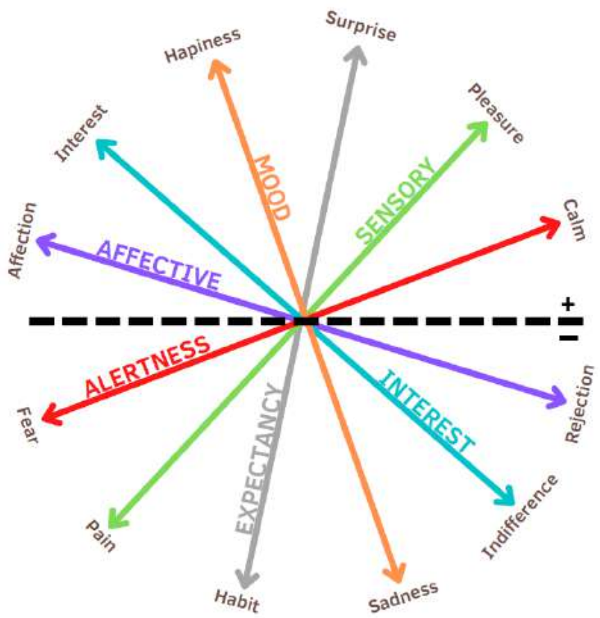



**Figure 2.4.** Representation of the emotions for the dimensional emotional model of Potato, proposed based on Plutchik's wheel of emotions [3][37].

#### 2.2.3.2. Facial Expression

The primary facial components used in social robots are mouth (lips), cheeks, eyes, and eyebrows. Most robot faces express emotion following Ekman and Friesen's Facial Action Coding System (FACS), which is a well-established method for categorizing human facial movements [38]. Some advanced robots incorporate mechatronic faces with multiple actuators working in concert to display specific emotions and can even incorporate hair, teeth, and a covering silicone skin layer.

However, in recent years an increasing number of robots have relied on **Liquid Crystal Display (LCD) screens** rather than physical mechanisms. Screens are cost-effective, flexible, and allow for nearly unlimited creativity in designing facial expressions. Consequently, there is a broad variety of robot faces with different levels of complexity and realism. Research by Kalegina et al. [39] indicates that **minimalistic faces** tend to be perceived as friendlier, more childlike, and suitable for roles in education, healthcare or entertainment.

**Color psychology** also plays a significant role, since colors can evoke different emotional responses and enhance the perception of robot's emotions [40]. For instance, blue is often associated with calmness and trust, while red can signify excitement or anger.

#### 2.2.3.3. Body Language

Non-verbal communication is often conveyed through gestures and body movement. Over 90% of gestures occur during speech, providing redundant information [41][42]. Most studies on emotional body movement have been qualitative, such as **Frijda's descriptions** of body movements for basic emotions that can be seen in Table 2.1 [11][43].

| Emotion | Body movement |
|---|---|
| Anger | Fierce glance; clenched fists; brisk, short motions |
| Fear | Bent head, trunk and knees; hunched shoulders; forced eye closure or staring |
| Happiness | Quick, random movements; smiling |
| Sadness | Depressed mouth corners; weeping |
| Surprise | Wide eyes; held breath; open mouth |

**Table 2.1.** Descriptions of body movements for basic emotions [11][43].

Body movement for expression transmission is highly related to cartoon animation. This principle has been ingeniously applied by **Disney Research** in the development of a bipedal **robotic physical character**, which is able to execute artist-directed animation motions thanks to reinforcement learning, creating a believable and engaging character [44]. The robot is shown in Figure 2.5 while interacting with a woman.

**Figure 2.5.** Disney Research bipedal robotic character interacting with a woman [44].

#### 2.2.3.4. Vocal Expressions and Non-verbal Sounds

In the realm of human-robot interaction, vocal expressions and non-verbal sounds play a crucial role in enhancing communication and interaction quality. Dialogue between humans and robots can take various forms, including natural language dialogue, and non-verbal sounds.

**Natural language dialogue** involves complex vocal expressions. Factors such as voice pitch, humor, and empathy significantly influence the interaction quality. Niculescu et al.'s study [45] highlights how voice pitch affects users' perception of a social receptionist, with higher-pitched voices being associated with more extroverted, humorous, and enjoyable interactions.

**Non-verbal sounds**, distinct from vocal expressions, include any audible sounds not involving words. These sounds can be used for explicit communication or to improve a robot's sociability, being a key component in multimodal human-robot interaction [46].

### 2.2.4. Manufacturing Materials and Techniques

#### 2.2.4.1. 3D Printing

3D printing has revolutionized the manufacturing industry, including the production of robots [44][47], by offering significant benefits such as **customization, rapid prototyping, and cost-effectiveness**. This technology allows for the creation of complex and tailored parts that would be difficult or impossible to produce with traditional manufacturing methods. It enables rapid prototyping, allowing designers to quickly iterate and test new ideas, significantly speeding up the development process.

The materials used in 3D printing have evolved over time, becoming more popular and less costly, which has further propelled the technology's adoption. Common materials are presented below and Table 2.2 shows the most relevant properties for each of them.

- **Polylactic Acid (PLA):** A biodegradable and easy-to-use material, popular for its low environmental impact and ease of printing. It is suitable for detailed prints but lacks durability and heat resistance.
- **Polyethylene Terephthalate Glycol (PETG):** Combines strength and flexibility, ideal for creating durable and functional parts. It resists warping and is more durable than PLA, though it can be trickier to print.
- **Acrylonitrile Butadiene Styrene (ABS):** It is valued for its durability and impact resistance, making it suitable for sturdy parts. It requires higher printing temperatures and proper ventilation due to fumes.
- **Thermoplastic Polyurethane (TPU):** It is a flexible, rubber-like material perfect for parts that need to bend or stretch. It offers excellent abrasion resistance and durability, making it ideal for wearable items and flexible components.

| Property | PLA | PETG | ABS | TPU |
|---|---|---|---|---|
| **Biodegradability** | Partly | Non-biodegradable | Non-biodegradable | Non-biodegradable |
| **Recyclable** | Yes | Yes | Yes | Yes |
| **Ease of Printing** | High | Medium | Low | Medium |
| **Tensile Strength (MPa)** | 65 | 53 | 40 | 26–43 |
| **Density (g/cm$^3$)** | 1.24 | 1.23 | 1.04 | 1.19–1.23 |
| **Heat Resistance (°C)** | 52 | 73 | 98 | 60–74 |
| **Flexibility** | Low | Medium | Low | High |
| **Chemical Resistance** | Low | High | Medium | High |
| **UV Resistance** | Low | Medium | Low | High |

**Table 2.2.** Properties of 3D Printing Materials: PLA, PETG, ABS, and TPU [48][49].

#### 2.2.4.2. Soft Materials

Soft materials are becoming increasingly common in robotics due to their safety and enhanced interactivity. These materials provide a more lifelike and approachable experience, essential for robots designed to interact closely with humans. By using soft materials such as **silicone, foam, and soft textiles**, robots can mimic tactile qualities of human skin or fur, making them feel **more friendly** and less mechanical [50]. They also make robots more huggable and less intimidating, fostering positive interactions and emotional bonds. Some examples are Tega and Paro, which can be seen in Figures 2.7b and 2.8a respectively in the next section.

## 2.3. Applications and Case Studies of Social Robots

Social robots have become integral across various domains due to their ability to interact with humans in meaningful ways. These robots are being employed to assist with daily tasks, provide companionship, aid in education, and even support medical procedures with a wide variety of designs and morphologies.

### 2.3.1. Personal Assistance

Personal assistance robots are increasingly becoming part of daily life, enhancing convenience and interaction beyond traditional voice assistants like Alexa. These robots help manage schedules, monitor home security, provide reminders, assist with household chores, and engage family members through natural voice commands and facial recognition. Some examples are Jibo, Zenbo and Buddy, which can be seen in Figure 2.6.

**(a)** **(b)** **(c)**

**Figure 2.6.** Examples of social robots used for personal assistance: (a) Jibo [51], (b) Zenbo [52], and (c) Buddy [53].

**Jibo**, introduced in 2017, assists with daily tasks, recognizes family members, manages schedules, and entertains children with interactive games and educational activities. **Zenbo**, from Asus, supports healthcare needs, controls household devices, reads recipes, and engages children with stories and games. **Buddy**, by Blue Frog Robotics, is designed to be an affordable companion robot to assist with daily routines, educate children, and monitor the home for security purposes.

### 2.3.2. Education and Child Development

Social robots are increasingly being recognized as valuable tools in classrooms and therapeutic settings. These robots offer interactive and personalized learning experiences, helping to engage children in educational activities and supporting developmental needs.

One prominent example is **NAO**, a humanoid robot developed by SoftBank Robotics [20]. NAO has been deployed in over 70 countries and 6,000 academic institutions, demonstrating its versatility as an educational tool. It aids in teaching STEM subjects, language learning, and social skills, catering to students from primary education to higher levels [54].

Another example is **Tega**, a social robot platform designed by MIT Media Lab's Personal Robots Group [55]. Tega supports long-term interactions with children, focusing on early literacy education through storytelling and vocabulary games. With its expressive capabilities and ability to interpret emotional responses, Tega provides personalized motivation and engagement strategies, enhancing the learning experience for young children.

**Moxie**, developed by Embodied [56], offers a wide range of activities to engage children in a meaningful play and learning. Moxie employs evidence-based therapeutic strategies to help children develop social, emotional, and cognitive skills through play-based learning and interaction sessions, monitored and guided by a companion app for parents [57]. This way it can support children with mental, behavioral, and developmental disorders (MBDDs). These three robots are shown in Figure 2.7.

**(a)** **(b)** **(c)**

**Figure 2.7.** Examples of education and child development social robots: (a) NAO [20], (b) Tega [55], and (c) Moxie [56].

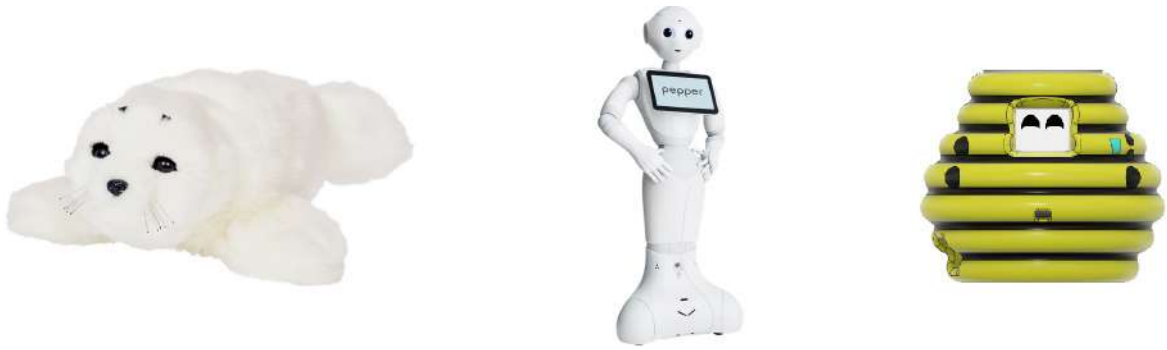
### 2.3.3. Healthcare and Elderly Care

Social robots in healthcare and elderly care are becoming increasingly important as tools to support the aging population. These robots provide companionship, cognitive stimulation, and health monitoring, aiming to enhance the quality of life for elderly individuals and support caregivers [58].

One notable example is **Paro**, a therapeutic robot designed to resemble a baby harp seal [18]. Paro has been used extensively in care settings for older adults, particularly those with dementia. Its soft tactile body and responsive behaviors help reduce stress, alleviate loneliness, and provide comfort, leading to improved mood and social interaction among users. Interactions with Paro in nursing homes have significantly reduced agitation and axiety in dementia patients.

Another example is **Pepper**, developed by SoftBank Robotics [19]. Pepper is a general-purpose humanoid social robot designed for social interaction. With advanced sensors and AI capabilities, Pepper can recognize faces, understand emotions, and engage in conversations. In healthcare, Pepper entertains, reminds patients about medications, and assists with simple tasks, helping to reduce feelings of isolation and stimulate cognitive functions [59] [60].

**BeeBot** is an innovative social robot aimed at children with diabetes and obesity [61]. BeeBot assists children in measuring their glucose levels and encourages healthy habits, such as drinking water and exercising. The robot is equipped with a glucometer, a water intake counter, and buttons that offer exercise recommendations and track daily goals. This accessible robot helps children become more comfortable with managing their health and supports parents in monitoring their child's progress through an app. Figure 2.8 shows these three examples.



**(a)** **(b)** **(c)**

**Figure 2.8.** Examples of healthcare and elderly care social robots: (a) Paro [18], (b) Pepper [19], and (c) BeeBot [61].

### 2.3.4. Entertainment and Companionship

Robots designed for entertainment and companionship are an emerging technology with growing interest, though they have yet to become a staple in most households. These robots offer engaging and lifelike experiences, often mimicking the behaviors of pets or characters to create a bond with their users. They pretend to serve as more than just toys, providing companionship and interaction.

One notable example is Sony's **AIBO**, a series of robotics dogs first introduced in the late 1990s [17]. Its last generation, ERS-1000, featured in 2018, features advanced AI capabilities, enabling it to recognize faces, understand voice commands, and develop a unique personality based on its interaction. Other robots like **Eilik** [62], developed by Energize Lab, or **Kiki** [63], by ZoeticAI, are small interactive companion robots that allow to play games, respond to touch, react to human emotions and develop a unique personality based on user interactions. Kiki has a particularly advanced emotional model based on leading psychology research and has its own needs and wants according to its personality. These three examples can be seen in Figure 2.9.


**(a)** **(b)** **(c)**

**Figure 2.9.** Examples of entertainment and companionship social robots: (a) Aibo [17], (b) Eilik [62], and (c) Kiki [63].

## 2.4. Social Robots Developed at CAR (UPM-CSIC)

Next, the three social robots that were developed by the Intelligent Control Group at CAR are presented in Figure 2.10. The functionalities and design of Urbano and Doris will be briefly described, while Potato will be detailed more extensively as it is the direct predecessor of the robot developed in this work.


**(a)** **(b)** **(c)**

**Figure 2.10.** Social robots built at CAR: (a) Urbano [1], (b) Doris [2], and (c) Potato [3].

### 2.4.1. Urbano

Urbano is an interactive **mobile tour-guide** robot with autonomous navigation capabilities using a laser scanner and sonar and infrared rings for obstacle detection [1]. It also has a mechatronic face and a robotic arm for expressing emotions. Urbano's standout feature is its ability to generate high-quality presentations tailored to different audiences using fuzzy logic and a genetic algorithm, continuously improving from audience feedback. It has been used in dynamic environments such as museums and educational settings.

### 2.4.2. Doris

Doris is an advanced social robot whose main objective is **information exchange in dynamic indoor environments** such as museums, theaters, trade fairs, and other public spaces [2]. It builds on the developments of previous robots like Urbano. Doris's hardware architecture includes a mobile platform, a skeleton replicating the human body, and a head capable of displaying various expressions. The software architecture integrates several subsystems including localization, path planning, mapping, emotional responses, and **lip synchronization**.

### 2.4.3. Potato

Potato is a compact, table-top robot whose primary goal is to facilitate the **testing of new capabilities for personal assistance and educational** social robots [3]. Due to its portable design, it allows easy programming and efficient testing, accelerating the development process. It is equipped with tactile and olfactory sensors, which significantly enhance its interaction capabilities.

The robot incorporates an **advanced emotional model based on fuzzy logic and social psychology**, developed in collaboration with psychologists. The emotional model includes three input stimuli: battery level, room brightness, and tactile feedback from caresses. These inputs affect the robot's emotional states, such as happiness or calmness, which are then expressed through physical responses like heartbeat frequency, facial expressions on a screen, and tail movement.

Potato's **software architecture** is based on a **socket communication** system and comprises six key modules: Arduino manager, face controller, emotional manager, speech analyzer, dialog manager, and knowledge database, coordinated by a **central state manager** that ensures seamless integration and communication among modules.

1. **Arduino manager:** Manages microcontroller operations, interfacing with sensors and actuators to ensure smooth hardware operation.
2. **Face controller:** Handles facial expressions for accurate and expressive displays.
3. **Emotional manager:** Analyzes sensor data to determine and generate emotional responses from the fuzzy logic emotional model algorithm.
4. **Speech analyzer:** Interprets vocal input to understand emotional cues.
5. **Dialog manager:** Oversees conversation flow, ensuring coherence and context.
6. **Knowledge database:** Stores information (user preferences, historical interactions, and contextual data) for decision-making and generating responses.

Chapter 3

# Methodology

This chapter outlines the methodology employed in the design and development of the robot. It begins by detailing the design tools used and next it discusses the hardware tools, essential for fabricating the robot components. The chapter also covers the firmware development tools, as well as the software development and deployment tools.

## 3.1. Design Tools

The three design software tools that were utilized in the project were: Autodesk Inventor, for 3D mechanical design and render generation; AutoCAD, for 2D manufacturing engineering drawings design; and Piskel, for generating the emotional faces animations.

### 3.1.1. Autodesk Inventor

Autodesk Inventor is a professional-grade Computer-Aided Design (CAD) software developed by Autodesk Inc., a pioneer in the software industry, particularly in the field of design and engineering [64]. Over the years, it has evolved into one of the most comprehensive and powerful tools for 3D design, simulation, and visualization, providing engineers and designers with advanced features for creating detailed and accurate digital prototypes. Its parametric design capabilities enable to create flexible and adaptable models, where changes in one part of the design are automatically propagated through the entire assembly, ensuring consistency and reducing time spent on manual updates.

It was chosen as the primary 3D design tool for this project because UPM provides **licenses** to its students and its workflow is similar to SolidWorks, a software already familiar. Moreover, Inventor's compatibility with other Autodesk software such as Fusion

360, facilitates the **future creation of Unified Robot Description Format (URDF) files**[1] necessary for robot simulation and control. Fusion 360 was considered but not used directly due to its cloud-based platform and broader capabilities, which were not required for the project's specific needs. Inventor was utilized extensively for various tasks:

- **3D modeling and assembly:** The software was used to create detailed 3D models of the robot's components ensuring all the pieces fitted together by grouping them into different sub-assemblies that compound the main robot assembly.
- **Simulation and analysis:** Inventor's simulation tools allowed for the testing of mechanical stresses, forces, torques, and movements within the design, highlighting any potential issues before physical prototyping. It also enabled to know the masses, volumes and moments of inertia of complex components.
- **Documentation:** The software facilitated the creation of comprehensive engineering drawings and documentation. This will be crucial for future manufacturing and assembly instructions.
- **Visualization:** Inventor's visualization capabilities enabled to create realistic renderings of the robot, aiding in the communication of design concepts and progress to stakeholders. In addition to the rendered images, a product **demonstration video** was created through Inventor Studio tool.

### 3.1.2. AutoCAD

AutoCAD, also developed by Autodesk Inc., is a leading software in CAD widely used in various engineering fields [65]. Originating in the early 1980s, AutoCAD has evolved to provide a robust platform for 2D and 3D design, drafting, and modeling. Its versatile tools and features enable precise and efficient creation of architectural plans, engineering schematics, and detailed mechanical parts.

AutoCAD was chosen for this project due to the licenses provided by UPM, and its compatibility with other Autodesk software. This program was used to create the 2D drawings for generating the Drawing Exchange Format (DXF) files for cutting some polystyrene pieces in the laser cutting machine.

### 3.1.3. Piskel

Piskel is an online editor designed for creating animated sprites and pixel art [66]. **Sprites** are two-dimensional images or animations integrated into a larger scene, commonly used in video games to represent characters, objects, or other elements. Sprites

[1] XML file used in robotics to describe the physical and visual properties of a robot model.

work by using a series of pre-rendered images, each depicting a different state or frame of an animation. These images, often arranged in a single file called a **spritesheet**, are displayed in sequence to create the illusion of motion. When a sprite is animated, the images are rapidly switched in a specific order and timing, which can be controlled by adjusting the frame delay. Figure 3.1 shows an example of a 2×7 spritesheet with two animations and seven frames or sprites for each animation [67].

**Figure 3.1.** Spritesheet example [67].

It was decided to use sprites to generate the robot's facial animations on the LCD display for several reasons:

- **Efficiency:** Sprites allow for pre-rendered, reusable images that can be quickly displayed, ensuring smooth and responsive animations without demanding high computational power.
- **Consistency:** Using sprites ensures that facial expressions are consistent and easily replicable, maintaining a uniform appearance across different animations.
- **Ease of creation and editing:** Tools like Piskel facilitate the creation and modification of sprites, enabling rapid prototyping and iterative design.
- **Memory management:** Spritesheets can be efficiently loaded into memory, reducing the resources needed for rendering animations compared to real-time generation.

Piskel was chosen for this project due to its user-friendly interface, live preview feature, and the ability to export in various formats like GIF and PNG. Its open-source nature allows for customization, and its offline versions support Windows, OS X, and Linux, making it versatile for different development environments.

## 3.2. Hardware Tools

This section outlines the essential hardware manufacturing tools used in this project, including 3D printers and a laser cutting machine. The specifications of the tools and methods applied will be briefly described.

### 3.2.1. 3D Printers

3D printing technology played a pivotal role in the fabrication process for this project. The primary 3D printer utilized was the **Prusa i3 MK3** [68] available in the lab. Additionally, another Prusa i3 MK3 unit and a Bambu Lab X1 Carbon [69] were employed for printing a few components at the residences of two lab members, all equipped with a 0.4 mm brass nozzle. Both 3D printer models can be seen in Figure 3.2.

**(a)** **(b)**

**Figure 3.2.** Used 3D printers: (a) Prusa i3 MK3 [68] and (b) Bambu Lab X1 Carbon [69].

The 3D printing pipeline began with the exportation of the **Standard Triangle Language (STL) files** from Inventor and the preparation of the 3D models using **Prusa Slicer**, a software that enables to convert digital designs into printable format or **G-code**[2]. The next key parameters that significantly affect print time and quality were adjusted for each component during slicing. The effects of each of them can be seen in Figure 3.3.

- **Layer height:** Determines the resolution and smoothness of the printed object. It was selected to be around **0.15 mm** for most pieces.
- **Infill density:** Sets the internal structure's density, balancing strength and material and time usage. Typically, densities range from 10% to 80%, with common settings around **20-40%** for a good balance.
- **Infill pattern:** Several infill patterns exist, such as grid, honeycomb, and **gyroid**. Gyroid for instance provides excellent strength-to-weight ratio and flexibility.
- **Support structures:** They are essential for overhangs and complex geometries, and they should be selected to be easily removable post-printing while ensuring enough stability. Among the different support styles available, **grid supports** provide a high stability but can be harder to remove and suppose a larger material use. On the other hand, **organic supports** branch out like a tree, providing support only where necessary, minimizing material usage and making removal easier.

[2] Language that directs CNC machines and 3D printers on movements and actions.

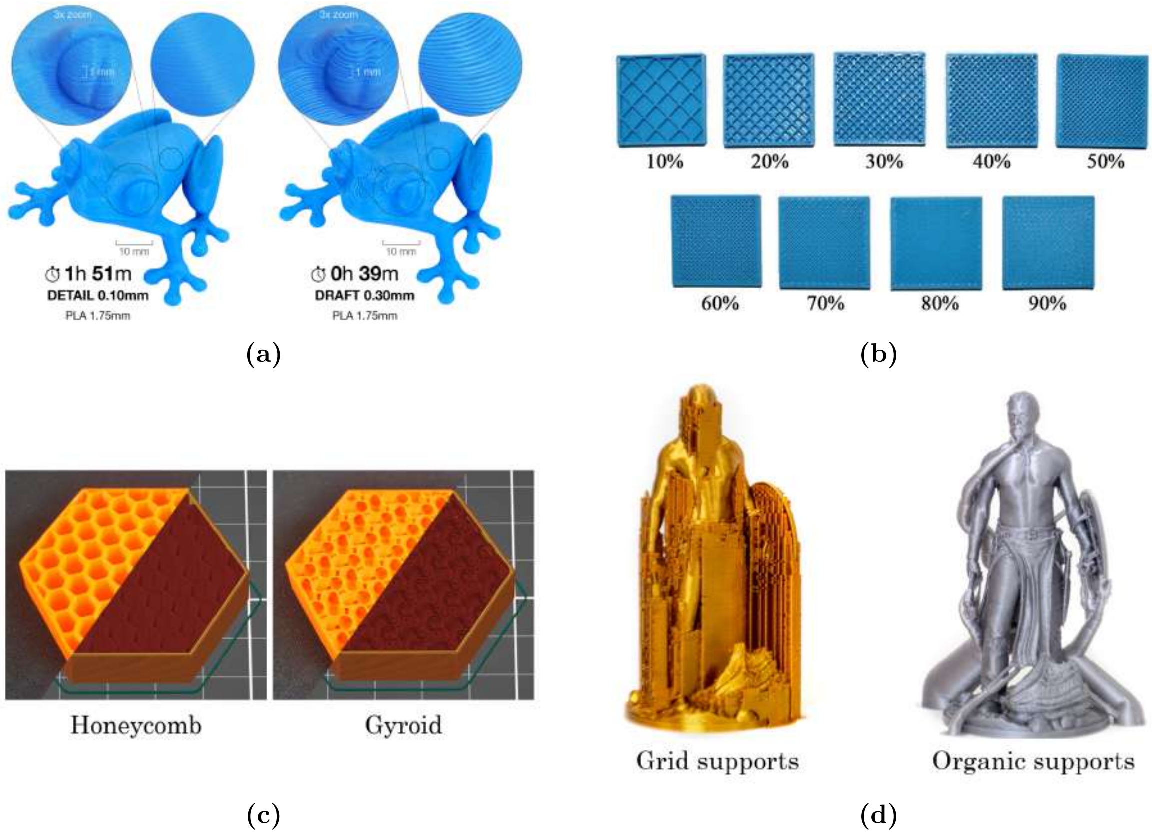
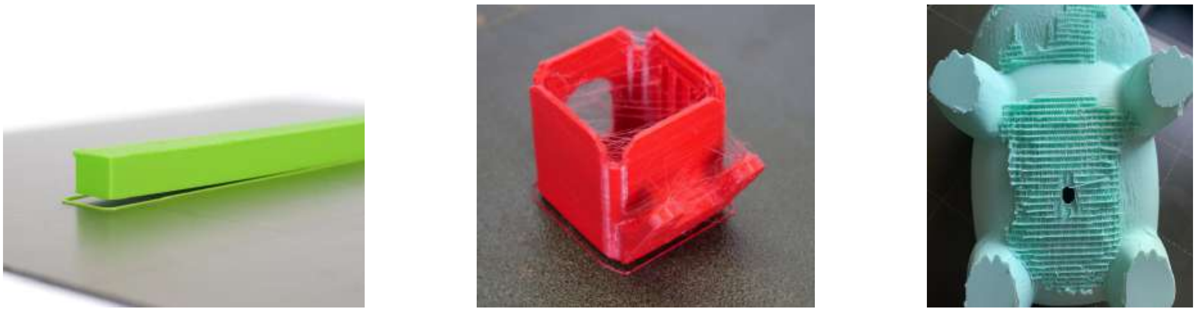



**Figure 3.3.** Effects of key 3D printing parameters: (a) Result comparison between 0.10 mm and 0.30 mm layers [70], (b) Comparison between different infill densities [71], (c) Honeycomb and gyroid infill pattern samples [72], and (d) Grid and organic supports comparison [73].

**PrusaLink** facilitated remote monitoring and control of the printer, essential due to the long print times required for the robot components. This tool allowed starting, stopping, and checking print progress from different locations through a local network connection via a Virtual Private Network (VPN), ensuring efficient use of time and resources. Additionally, a Universal Serial Bus (USB) **webcam** connected to a Raspberry Pi 4 running PrusaLink enabled remote viewing of the printing area to detect and address any printing issues promptly. During the printing process, the following common issues were encountered and addressed. Each of these issues can be observed in Figure 3.4.

- **Warping:** Occurs when the edges of a print lift off the print bed, causing deformation. This was mitigated by ensuring proper bed adhesion, for example adjusting the first layer height, and temperature settings.
- **Stringing:** Stringing happens when thin strands of filament are left between parts of print, resembling spider webs. This was reduced through fine-tuning retraction settings to prevent excess filament from oozing during non-print moves. Adjustments to the retraction speed and distance, as well as temperature optimization, helped minimize stringing.

- **Support Removal:** Removing support structures can be challenging and may damage the print if not done carefully. Different support types were tested to find the optimal balance between providing adequate support and ease of removal, being in most cases the organic style the most adequate.



(a) (b) (c)

**Figure 3.4.** Examples of commonly encountered 3D printing issues: (a) Warping [74], (b) Stringing [75], and (c) Hard-to-remove grid supports [76].

Finally, most 3D printed parts were **post-processed** to enhance their quality. To smooth the irregularities caused by the steps corresponding to each layer, putty was applied to the pieces and once dried they were sanded with varying grit level. By priming the pieces, the surfaces were prepared for painting to ensure better adhesion. Once painted, some pieces were varnished to protect the paint.

### 3.2.2. Laser Cutting Machine

For this project, the Laser CO2 FL5030 cutting machine was used once to cut a few **small polystyrene pieces** for robot's **Light Emitting Diode (LED) covering**. This desktop-sized laser cutter, located at FabLab ETSIDI, is capable of handling various non-metallic materials such as acrylic, wood board, and methacrylate. The laser diameter is approximately 0.4 mm, and it can cut polystyrene up to 3 mm thick.

To prepare the files for the cutting machine, a technical drawing was created in AutoCAD. This drawing accounted for the necessary resizing to consider the laser diameter and followed the required format to avoid any issues. The file was then exported in DXF format, and the pieces were cut with the required quality.

## 3.3. Firmware Tools

This section covers the firmware tools used in this project, focusing on Arduino and the communication protocols utilized to interface with various components and sensors. Firmware third-party libraries are detailed in Chapter 6.

### 3.3.1. Arduino

Arduino is an **open-source electronics platform** based on easy-to-use hardware and software [77]. In this project, an Arduino microcontroller was employed to manage the robot's **sensors and actuators**. The simplicity and flexibility of Arduino make it ideal for rapid prototyping and educational purposes, offering extensive libraries and a supportive community. Arduino additionally has an **extension for Visual Studio Code**, one of the most popular Integrated Development Environments (IDEs), providing a robust environment for writing, debugging, and uploading sketches to the Arduino microcontroller. There are different available Arduino boards each offering unique features suited for different applications such as Arduino Uno, Arduino Nano or Arduino Mega 2560.

### 3.3.2. Communication Protocols

To enable efficient communication between the Arduino microcontroller and other components, several communication protocols were used. These protocols ensure reliable data transfer and coordination among the various parts of the robot.

#### 3.3.2.1. Universal Asynchronous Receiver-Transmitter (UART)

UART is a hardware communication protocol used for serial communication. It is the primary method used to **upload firmware** to the Arduino from the development environment. When a sketch is uploaded, it is transmitted over a USB-to-UART bridge to the microcontroller. Additionally, UART facilitates serial communication for **debugging and monitoring** purposes, allowing real-time data exchange and troubleshooting.

#### 3.3.2.2. Inter-Integrated Circuit (I2C)

I2C is a multi-master, multi-slave, packet-switched, single-ended, serial communication bus. It is widely used for attaching lower-speed peripheral integrated circuits to processors and microcontrollers. In this project, I2C was utilized for communication between the Arduino and various **sensors**. The advantage of I2C is its simplicity and ability to connect multiple devices using only two wires, Serial Data Line (SDA) and Serial Clock Line (SCL), reducing the complexity of the wiring.

#### 3.3.2.3. General-Purpose Input/Output (GPIO)

Though not formally a communication protocol, GPIO pins are **versatile pins** on a microcontroller that can be configured as input or output. These pins are essential for interfacing with various components, such as LEDs, buttons, and motors. The flexibility of GPIO pins allows them to be used for a wide range of applications, making them a crucial part of the microcontroller's interfacing capabilities.

## 3.4. Software Development and Deployment Tools

This section outlines the software tools utilized in developing and deploying the robot's firmware and higher-level software. The tools were selected for their compatibility, efficiency, and robust development workflows. Figure 3.5 shows a summary of the software development and deployment tools used in the project.

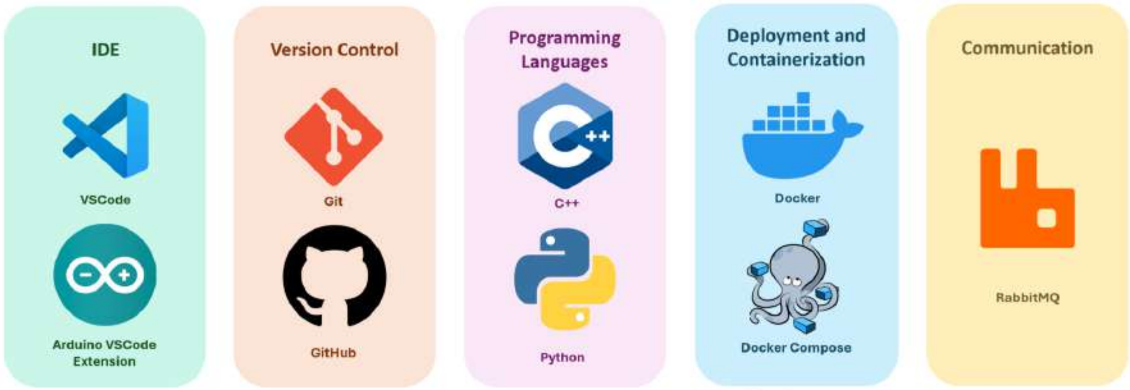



**Figure 3.5.** Summary of software development and deployment tools used in the project.

### 3.4.1. Development Environments and Tools

The development of the robot's software and firmware leveraged a range of tools and programming languages, each chosen for their suitability to specific tasks within the project.

#### 3.4.1.1. IDEs and Version Control

For this project, Visual Studio Code (VSCode) was the primary Integrated Development Environment (IDE) used [78]. **VSCode** offers a rich set of features such as syntax highlighting or integrated debugging, making it ideal for both firmware and software development. Additionally, the **Arduino extension** for VSCode was utilized to streamline the development of the firmware.

Version control was handled using Git, with GitHub as the remote repository, facilitating collaboration and ensuring robust version management. **Git** is a distributed version control system that allows multiple developers to work on a project simultaneously, tracking changes and maintaining a history of modifications [79]. **GitHub** is a cloud-based platform that hosts Git repositories, providing tools for version control, collaboration, and project management [80].

#### 3.4.1.2. Programming Languages

The **firmware** of the robot was developed using **C++** following Object Oriented Programming (OOP) principles. C++ was chosen for its efficiency and control over hardware resources, which is crucial for real-time embedded systems [81]. **OOP** is a programming paradigm based on the concept of "objects", which can contain data in the form of fields (attributes or properties) and code in the form of procedures (methods). The key principles of OOP include **encapsulation**, which bundles data and methods into a single unit, **inheritance**, which allows a class to inherit properties and methods from another class, and **polymorphism**, which enables objects to be treated as instances of their parent class.

The **higher-level software modules** were developed in **Python**. Python's simplicity and extensive libraries make it an excellent choice for rapid development and integration of various software components [82]. The software architecture was also written following OOP principles in Python. This approach enhances code maintainability and reusability, essential aspects for developing robust and scalable systems.

### 3.4.2. Deployment and Containerization Tools

This section covers the tools and technologies used for deploying and managing the software environment of the robot. Deployment and containerization tools are essential for ensuring that applications run consistently across different systems, facilitating easy replication and scaling of environments.

#### 3.4.2.1. Docker and Docker Compose

Docker and Docker Compose were employed to ensure consistent development and deployment environments across different systems. Docker is a platform that uses operating system level virtualization to deliver software in packages called containers, ensuring applications run consistently across different environments [83]. Docker Compose, on the other hand, is a tool for defining and running multi-container Docker applications, particularly useful for managing complex applications with multiple interconnected containers, streamlining development and deployment processes [84].

In this project, **Docker** was used to create lightweight, portable containers that encapsulated the application and its dependencies. This ensured that the software ran identically regardless of whether it was on development computers or the local processing unit of the robot. **Docker Compose** facilitated the orchestration of multiple containers, including a master one in charge of message brokering[3], and then one for each software architecture module: Arduino manager, face controller, speech analyzer, emotional manager, dialog manager, and knowledge base. Passing from the original Potato's socket communication to this container approach was the core of a different Master's Thesis carried out in the lab, but this information is relevant to the project since the demo for the robot developed in the present work was programmed following this architecture in a separate container.

#### 3.4.2.2. Robot Operating System (ROS)

Although **ROS was not directly implemented in the robot**, its architecture greatly inspired the design of the **software**, particularly in the use of **messages and topics for inter-process communication**. ROS is a flexible open-source framework for writing robot software [85]. It is a collection of tools, libraries, and conventions that aim to simplify the task of creating complex and robust robot behavior across a wide variety of robotic platforms.

In a ROS-based system there are typically many nodes, each responsible for a modular component of the system that performs a certain computation. Nodes can communicate with each other by passing messages. A **message** is a data structure comprising typed fields, for example integers, floating-point numbers, arrays, and more complex data structures. **Topics** are named buses over which nodes exchange messages. A node can publish a message to a topic or subscribe to a topic to receive messages. This decoupling of data production and consumption facilitates modularity and scalability.

The decision to create a custom firmware and software architecture not only simplifies the learning curve for new people working on the robot, but also provides the advantages of having a tailored solution that meets the specific needs of the project. Some of these advantages are:

- **Efficiency:** Tailored firmware can be optimized specifically for the hardware, potentially resulting in better performance and lower resource consumption compared to a more general-purpose system like ROS.
- **Control:** Custom firmware allows for complete control over the robot's operation.
- **Size:** A custom firmware can be much smaller in size since ROS includes many features and tools that are not necessary for this project.
- **Dependencies:** ROS requires a number of dependencies and specific software versions that can complicate setup and maintenance.

[3] Process of managing and facilitating communication between different applications by handling the transmission of messages.

#### 3.4.2.3. RabbitMQ

RabbitMQ was employed for **message brokering** in the robot's software architecture. It is an open-source message broker that facilitates the exchange of information between different parts of the system by sending messages via queues [86]. RabbitMQ implements the Advanced Message Queuing Protocol (AMQP), an open protocol designed for reliable, scalable, and flexible message-oriented middleware.

AMQP ensures that messages are delivered reliably, supports various messaging patterns, and allows for the secure transmission of messages between different system components. It uses a producer-consumer-broker model, where producers send messages, consumers receive them, and the broker routes messages from the producers to the appropriate consumers using queues. Exchanges within the broker help determine how messages should be routed following different patterns: direct (exact match routing), topic (pattern-based routing), and fanout (broadcasting to all queues). It also supports message acknowledgment, ensuring that messages are properly received by customers. Security is achieved through encryption (using Transport Layer Security (TLS)) and authentication mechanisms, which protect the communication and control access to the messaging infrastructure.

In this project, RabbitMQ handles the communication between different software modules (such as Arduino manager or face controller) by acting as a central message broker running in the master container of the application. This setup ensures reliable and efficient message passing, crucial for coordination and integration of the robot's various functionalities.

Chapter 4

# Robot Design

This chapter provides a comprehensive overview of the design process undertaken to develop the robot presented in this work. It details the systematic approach from the initial conception to the final detailed design, covering all aspects of mechanical, electrical, and aesthetic design.

## 4.1. Concept Design

This phase is crucial as it lays the foundation for the entire development process. This stage involves brainstorming, sketching initial ideas, and defining the core objectives and functionalities of the robot.

### 4.1.1. Functional Requirements

First, clear design functional requirements were established to ensure that the final product meets the intended goals. The design requirements for the robot were determined based on the desired functionalities, user interactions, and future applications. In addition to this, certain **specific requirements** were set by the lab members that organized the social robot **design contest**. Table 4.1 shows the identified requirements.

### 4.1.2. Initial Sketches and Ideas

The initial phase of the robot design process involved **brainstorming and sketching** to visualize potential concepts and functionalities. These sketches aimed to establish the robot's basic structure, appearance, and interactive features. Several rough sketches

| Requirement | Description |
|---|---|
| **Compactness and stability** | The robot must be lightweight and compact to facilitate easy transportation by a single person and placement on any flat surface. |
| **Maintenance** | The robot prototype, designed for research purposes, should allow easy access to components for maintenance and repairs, especially to the battery for recharging. |
| **Power management** | The robot must be able to operate both plugged in and on battery power, with a battery life of at least 2 hours. |
| **Air refrigeration** | The design must ensure proper air circulation to cool the processing unit effectively. |
| **User-friendly and ergonomic design** | The robot's appearance should be approachable and friendly, appealing to users of all ages, especially those aged 6 to 15, and should be ergonomic and comfortable to interact with. |
| **Cost optimization** | Costs must be optimized, well-justified, and balanced with maximizing its functionalities. |
| **Flexibility** | The robot hardware should be flexible to enable future upgrades while maximizing its capabilities for its use in different research projects. |
| **Customization** | The robot should support customization to adapt to different user preferences and environments. It should also show the CAR logo in its front part. |
| **Emotion display** | The robot must clearly display basic emotions through facial expressions or movements to engage effectively with users. |
| **Ease of assembly** | The robot should be easy to assemble and disassemble to facilitate maintenance and potential upgrades. |
| **Component integration** | **Compulsory components:**<br>- Arduino Mega 2560<br>- NVIDIA Jetson TX2i (processing unit)<br>- 7" LCD display<br>- 1 TB Solid State Disk (SSD)<br>- 4-microphone array and speakers<br>- USB hub<br>- Lithium-ion battery<br>- External connection ports and power switch<br>- Actuators: Motors and LEDs<br>- Sensors: Tactile and Light Dependent Resistor (LDR)<br>**Optional components:**<br>- Leap Motion Controller<br>- Intel RealSense D405 camera<br>- Samsung Galaxy A8 tablet |
| **Minimum functionalities** | The users must be able to:<br>- Caress the robot<br>- Interact with at least one robot mobile part<br>- Talk with the robot (audio input and output)<br>- Perceive the robot's pulse |

**Table 4.1.** Identified robot design functional requirements.

were drawn to explore different shapes and forms the robot could take. The sketches included various expressions and movements the robot could perform to display emotions effectively, as this was a key functional requirement.

Several iterations of these initial sketches were made, focusing on the location of each of the hardware components and ergonomics to achieve the best user experience. Concepts for mobile parts, such as movable head and arms, were explored to make the robot more dynamic and engaging. These initial drawings, some of which can be seen in Figure 4.1, laid the groundwork for more detailed designs and eventual 3D modeling.

The idea to add **arms or a tail** to the robot **was discarded** since it would be adding unnecessary complexity to the design. Though **antennas** were not initially included in the design, it was thought they might be useful for transmitting **emotions** more effectively, as it was seen in externally developed robots such as Reachy, by Pollen Robotics [87], or Disney Research's bipedal robot [44].

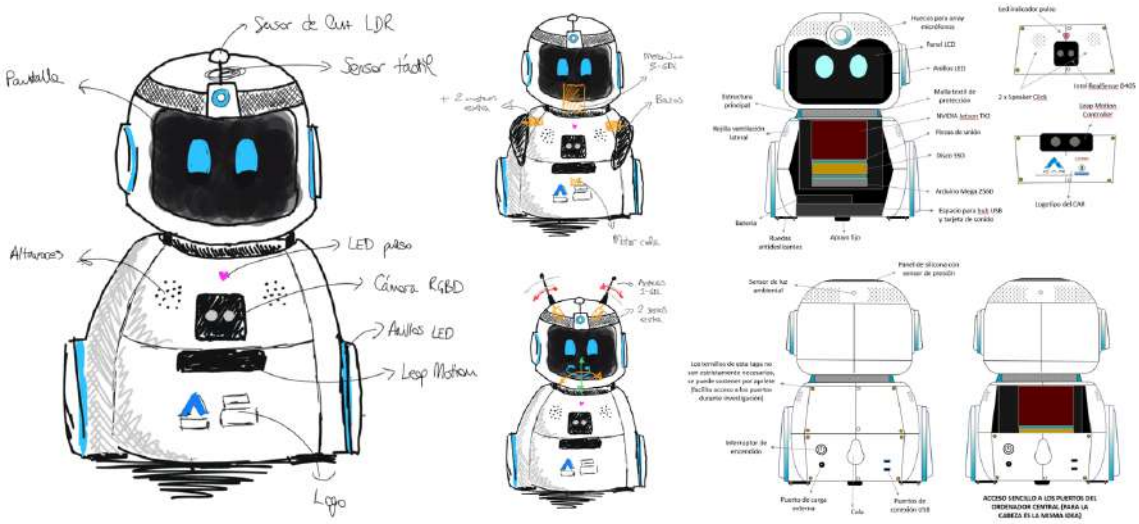


**Figure 4.1.** Examples of sketches and ideas from the design process.

### 4.1.3. Design Considerations

In this section, the concept design of the robot is explained and justified. The key aspects considered during the design process include user interaction and ergonomics, aesthetics and safety features.

#### 4.1.3.1. User Interaction and Ergonomics

User interaction was a primary focus during the design phase. The robot was designed to facilitate intuitive and engaging interactions with users. Ergonomically, the robot stands around **40 cm tall** (50 cm with the antennas in vertical position) and has a **diameter of approximately 30 cm**. These dimensions ensure an optimal size for the intended applications, as shown in 4.2.

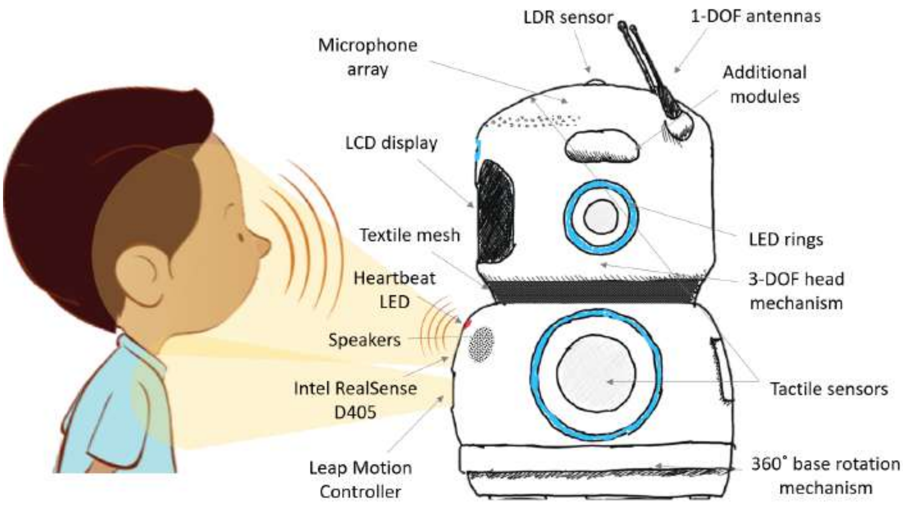



**Figure 4.2.** Concept design HRI.

The design features **two main parts: the body and the head**. Given its role as a social robot for research, the design is **modular** to allow easy access to components. This modularity enables the robot to accommodate more sensors than strictly necessary and allows for easy disassembly for maintenance and upgrades.

To enhance emotional and social interaction, the design includes an **Intel RealSense D405 camera** at the front for object and facial recognition. Additionally, a **Leap Motion Controller** is positioned lower on the front to track hand gestures, enabling interactions like sign language. The robot also includes a **LDR sensor** on top of the head and **five tactile sensors** located on the head and body. **Extra sensors and actuators can be attached modularly** on both sides of the head, allowing for future upgrades. The **servomotors** in the antennas provide torque feedback, enabling them to function as both actuators and **sensors**.

The design includes **six Degrees Of Freedom (DOF)**: a **rotating base** for 360° orientation, a **3-DOF neck mechanism** for pitch, roll, and yaw, and one DOF per antenna. This extensive actuation system ensures a wide range of movements, enhancing the robot's expressiveness.

The robot features **two speakers** on the front panel and a **heartbeat LED** indicator above the camera. **Five LED rings**, along with the LCD display, sounds, and body posture, help convey the robot's emotions. The **4-microphone array** is located on top of the head to minimize noise interference from the NVIDIA processing unit's fan.

#### 4.1.3.2. Aesthetics

The robot's face design integrates a rectangular **LCD display** with a curved, complex geometry, giving its a modern, futuristic appearance. The primary colors used in the design are white and black, enhancing its minimalistic look. The white body provides a clean, approachable aesthetic, while black accents on features like the LCD display and sensors add a touch of contrast and depth.

The front lower panel prominently displays the CAR (UPM-CSIC) **logo** beneath the Leap Motion Controller, ensuring visibility and institutional branding.

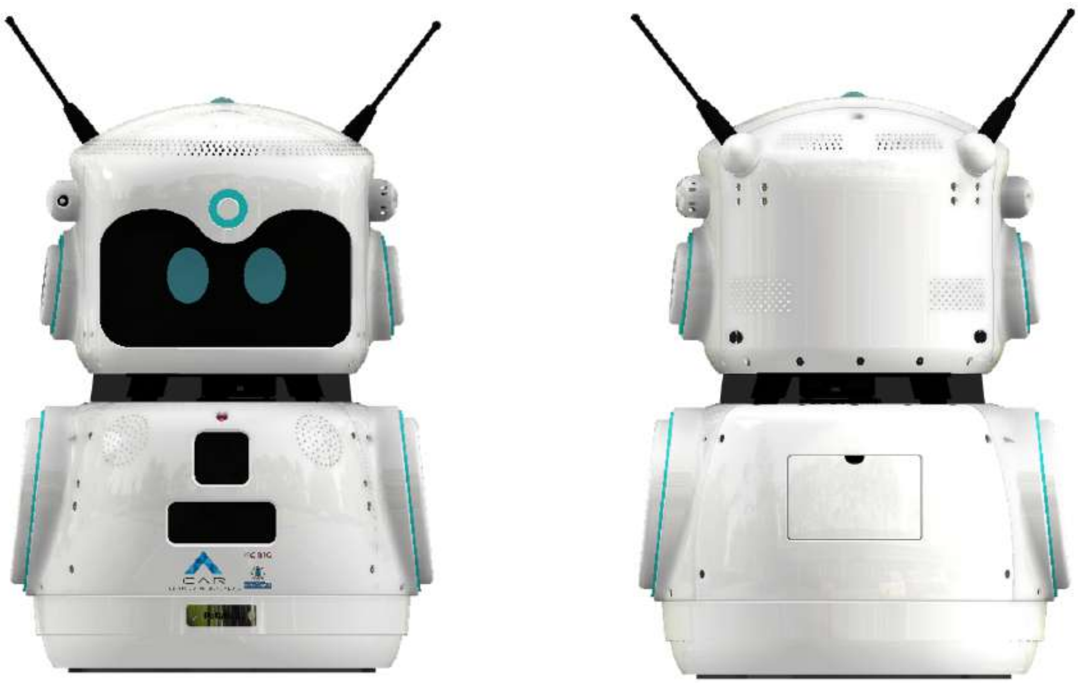
#### 4.1.3.3. Safety Features

Safety is paramount, especially since the robot will interact with children aged 6 to 15 years. An **elastic textile mesh** in the neck prevents children from inserting their fingers between the body and the head while enhancing the robot's aesthetic appeal. This mesh also allows air circulation to cool the NVIDIA Jetson TX2i processing unit.

The design includes a **covered port panel** at the back with all the required ports and switches. Finally, the **battery** is easily accessible yet protected, located on the robot's right side under a magnetically attached cover, facilitating recharging while maintaining safety.

## 4.2. Mechanical Design

Building upon the foundational concept design, the mechanical design phase focuses on detailed engineering of the robot's physical components. This section outlines the structural components and mechanisms that enable the robot to function effectively and interact with its environment. It can be decomposed into **six submodules**: the base, the body, the neck 3-DOF mechanism, the head, the antennas and the extra modules. The **technical drawings** for each of these submodules can be consulted in Appendix A. Figure 4.3 shows the detailed design of the robot.



**(a)** **(b)**

**Figure 4.3.** Social robot's detailed design: (a) Front, (b) Back.

### 4.2.1. Base

The base enables the whole robot to yaw and orient in any direction while supporting its weight. This sub-assembly is independent from the body structure and can be easily assembled through six bolts. The base is made up of two main components, the lower platform, which is fixed to the ground thanks to **anti-slip adhesives**, and the upper platform, which rotates with respect to the first one. The robot can rotate **unlimited full 360° turns** because the motor connected to the microcontroller is attached to the rotating platform of the base. Figure 4.4 shows the base sub-assembly.

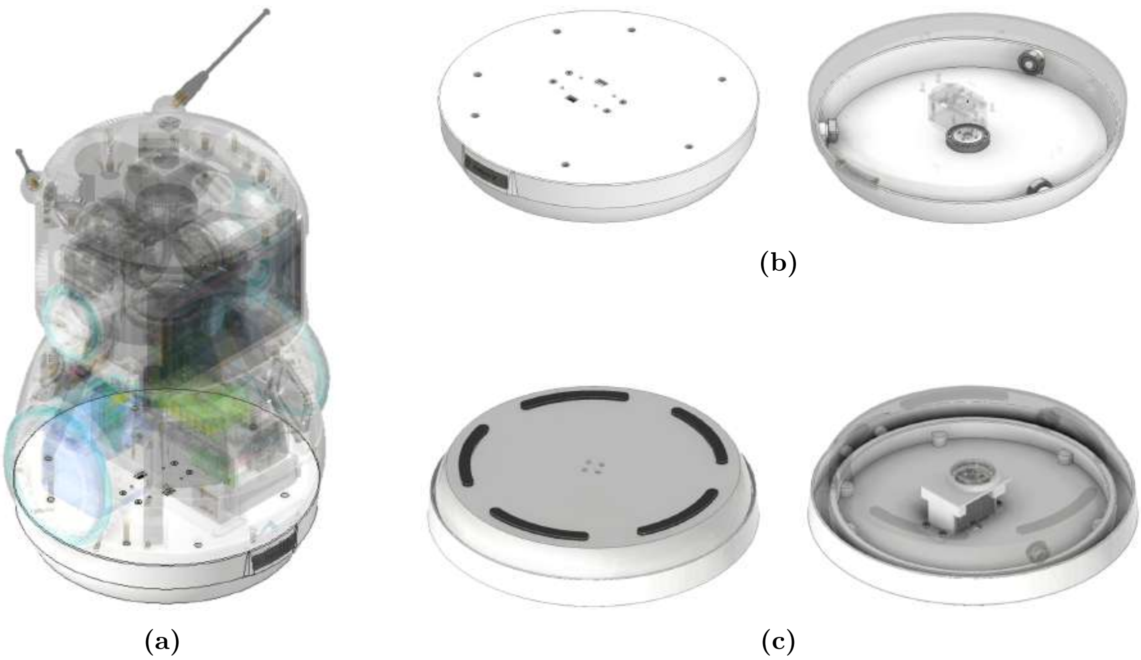
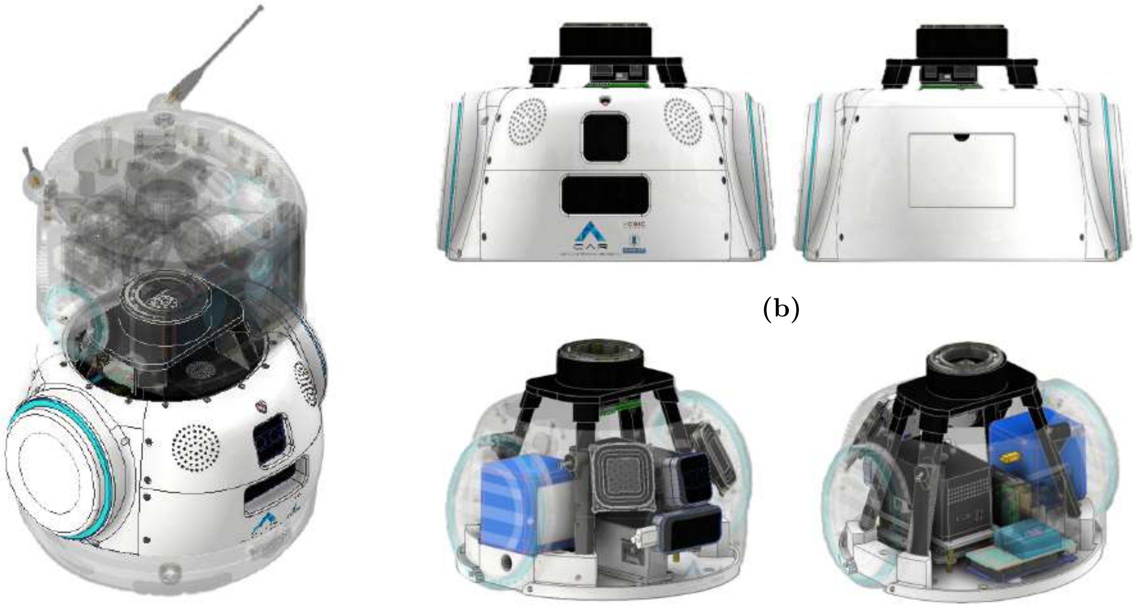


**Figure 4.4.** Robot base sub-assembly: (a) Location in the main assembly, (b) Top view detail, (c) Bottom view detail.

In order to **homogeneously distribute the weight** along the base, three 8×22×7 mm bearings were disposed in a triangle in the external ring and a bigger 25×37×7 mm bearing was located in the center to avoid the servomotor to suffer excessive axial load. A couple of holes were designed in the front of the base for screwing a **plate with the robot's name** (Potato 2 by the moment) and another couple of holes were made in the top platform to enable the passing of the servomotor's cables. For the threaded unions, M3 and M5 threaded inserts were used.

### 4.2.2. Body

The body sub-assembly is where the most relevant hardware components are located, so it has been designed for them to be easily accessible. It consists of a base platform, a **4-leg structure** to support the neck mechanism and the head, and several external covers. The lateral external panels are fixed to the legs of the support structure and the front and back panels can be easily disassembled to access the internal components by retiring a few bolts. Additionally, by retiring the **magnetically attached** lateral right cover it is possible to comfortably retire the battery for recharging without the need of retiring any bolt. Figure 4.5 shows an overview of the body sub-assembly.



(a) (b) (c)

**Figure 4.5.** Robot body sub-assembly: (a) Location in the main assembly, (b) External front and back views, (c) Internal detail views.

#### 4.2.2.1. Support Structure

The support structure consists of a base platform that is threaded to the base sub-assembly and which has different holes to locate the internal hardware elements. The four legged-supported platform holds a servomotor in charge of the yaw rotation of the head, limited to around $\pm\mathbf{25}°$ because of the neck textile mesh. A 45×75×10 mm bearing is used for transmitting the axial load from the head to the support structure without overloading the servomotor. Figure 4.6 shows the details of the structure.

(a) (b)

**Figure 4.6.** Details of the support structure: (a) Front and right views, (b) Motor detail.

#### 4.2.2.2. Front Panels

The two front panels are threaded to the lateral ones and hold the Leap Motion Controller and the Intel RealSense D405 camera with the desired orientation for proper human-robot interaction. In addition to this, the upper panel holds the two speakers and the heartbeat LED and the lower panel showcases the institutions logos. The camera is assembled by retiring a cover under the upper panel as it can be seen in Figure 4.7.

(a) (b)

**Figure 4.7.** Details of the front panels: (a) Front and back views, (b) Assembly details.

#### 4.2.2.3. Back Panel

The back panel is threaded through four bolts to the lateral panels of the body. It has five additional bolts for fixing the elastic textile mesh and a **magnetic cover** that protects the ports panel. The details of the back panel can be observed in Figure 4.8.


(a) (b)

**Figure 4.8.** Details of the back panel: (a) Front and back views, (b) Port panel details.

The port panel includes a **mode switch** that enables to choose between battery and plug-in mode, a **power button** for turning the robot on and off, an **Ethernet** port, **two USB-C ports**, a **power port** to connect the robot to the socket through a transformer, a **button** to reset the Arduino and a **4 A fuse**. The fuse is an extra safety component that will limit the maximum amount of current consumed by the robot to ensure that components like the battery are not damaged. The fuse could also be substituted by an emergency button to be used during testing.

#### 4.2.2.4. Lateral Panels

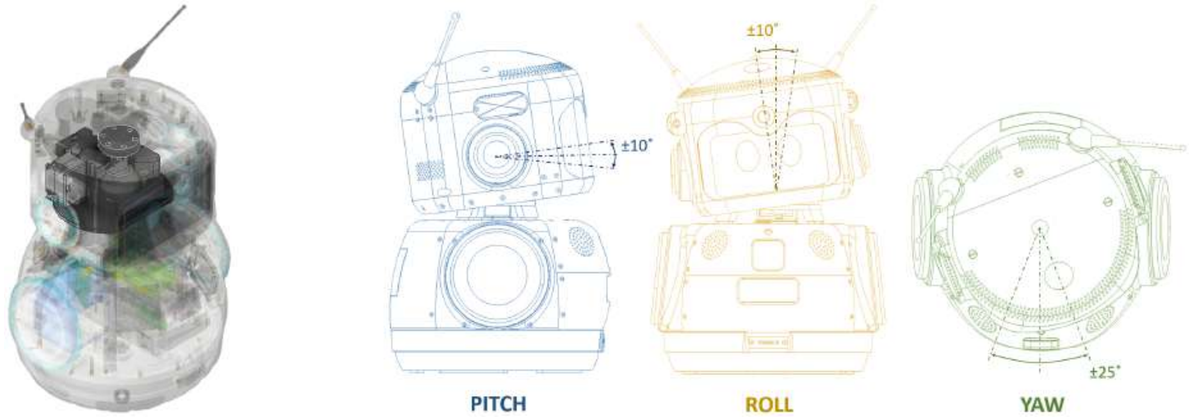
The right and left lateral panels are symmetric and consist of a main body with a cover. Each body includes the holes to thread them to the rest of the sub-assembly though threaded inserts and has **embedded magnets to attach the cover**. Each cover holds a circular **silicone tactile sensor** and each panel body holds a circular 40-LED ring, whose light will be diffused thanks to a polystyrene ring located at the optimal distance. Figure 4.9 shows the details of the body lateral panels.

**(a)** **(b)**

**Figure 4.9.** Details of the lateral panels: (a) Front and back, (b) Side view and cut view.

### 4.2.3. Neck Mechanism

For enabling the 3-DOF, several neck mechanism alternatives were studied. The alternatives could be differentiated in two groups: serial mechanisms and parallel mechanisms. **Serial mechanisms** are easy to control but normally present lower stability and precision than parallel mechanisms. On the other hand, **parallel mechanisms** can support greater load and are generally more precise and stable but their control is more complex. Since in the case of this robot design the head was expected to be quite heavy (around 2-3 kg), it was initially decided to use a parallel mechanism, a 2-DOF Spherical Parallel Manipulator (SPM). However, finally the neck mechanism was redesigned since the initial design presented several limitations as explained in Section 5.2.3. Both designs are detailed and explained in the following sections. Figure 4.10 shows the location of the mechanism sub-assembly and the ranges of motion for each DOF.




(a) (b)

**Figure 4.10.** Details of the neck mechanism: (a) Location in the main assembly, (b) Ranges of motion for each DOF.

#### 4.2.3.1. Initial Design: 2-DOF SPM

The initial design was inspired by the Omni-Wrist III mechanism [88][89], invented by Ross-Hime Designs, Inc. This is a well-known 2-DOF wrist mechanism that incorporates parallel links with double universal joints. It has the advantage of singularity-free operation over the entire hemispherical work-space and maintains a constant axial distance between the two joints [90]. Though the two motor **inputs are coupled**, the forward and inverse kinematics for the position and velocity of the mechanism have already been solved, enabling the control of the SPM. The upper platform of the mechanism includes several holes for supporting the head components as it can be seen in Figure 4.12.

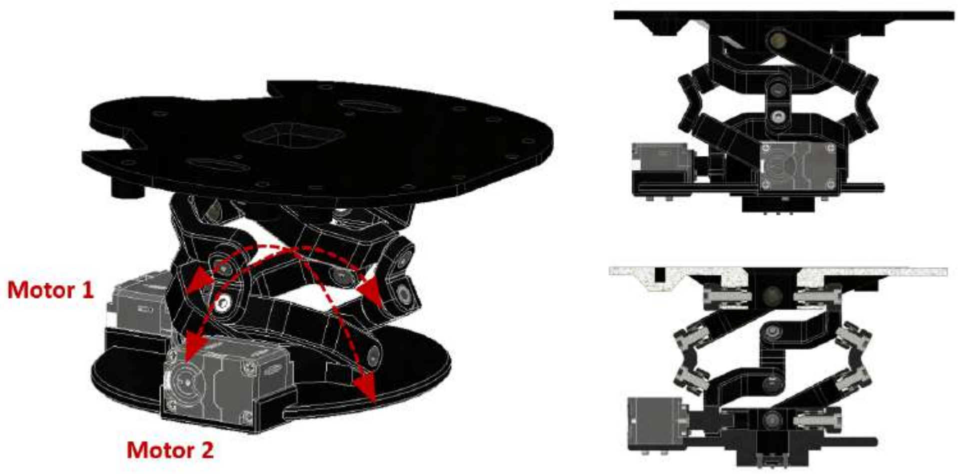



**Figure 4.11.** Actuation and details of the 2-DOF SPM.

The different arms components are linked together with roller bearings to ensure smooth functioning and minimize friction losses. The center hole of the mechanism could be used for passing the cables from the head to the body.

#### 4.2.3.2. Final Design: 2-DOF Spherical Gear Mechanism

The final design is a novel serial mechanism that enables to transmit the head load directly to the body support structure without overloading the servomotors. It was inspired by the ABENICS mechanism [91], a 3-DOF active ball joint mechanism consisting of a spherical gear actuated through four motors which can transmit high torque and reliable positioning. The details of the final neck mechanism design can be seen in Figure 4.12.

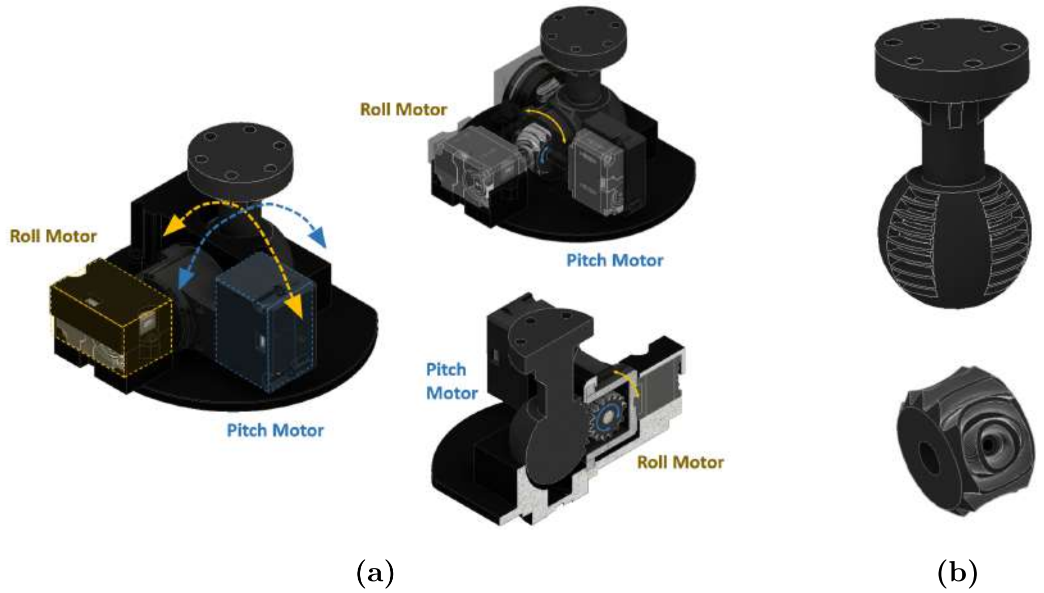
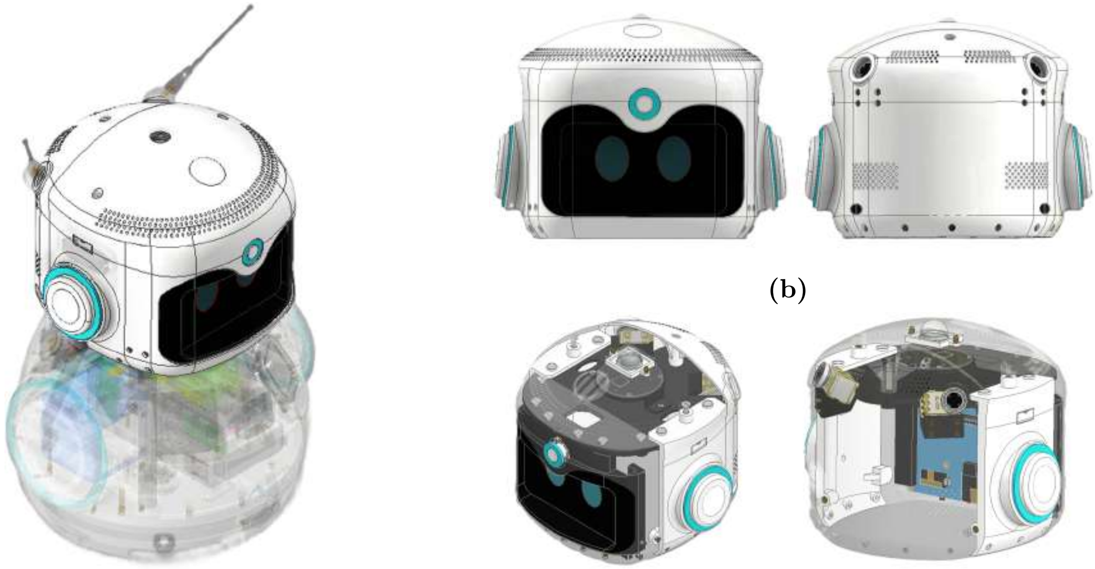



**Figure 4.12.** Details of the 2-DOF Spherical Gear Mechanism: (a) Mechanism actuation, (b) Spherical gears detail.

The proposed design is a simplified version of the ABENICS mechanism, with only two DOF instead of three. The actuation is made over a spherical gear to which the head is threaded. The roll motor rotates the tilting pitch motor together with the spherical pinion, while the pitch motor actuates over the axis of the spherical pinion. This enables to have both motors **decoupled** easing the control with respect to the initial design. An extra free spherical pinion was added to half the weight transmitted from the head to the support structure on each of the pinions. Two 45×58×7 mm and three 8×12×3.5 mm bearings are used for smooth non-axial and axial rotation of the spherical pinions, respectively. The spherical gear was designed to only have teeth in the spherical pinon directions to avoid uncontrolled yaw rotation. The mechanism is additionally able to maintain the head in a fixed position even when the motors are turned off and permits a **±10° pitch and roll** rotation without collision between the head and the body.

### 4.2.4. Head

The head sub-assembly also holds several hardware components and is the most characteristic part of the robot. It consists of a structural support platform that is threaded to the mechanism spherical gear and to which different external panels are attached through threaded inserts. Figure 4.13 shows the head design.



(a) (b) (c)

**Figure 4.13.** Robot head sub-assembly: (a) Location in the main assembly, (b) External front and back views, (c) Internal detail views.

#### 4.2.4.1. Structural Support

The head structural support platform serves to fix all the external panels together. As it can be seen in Figure 4.14, it has two elliptical holes for the cables proceeding from the lateral panels corresponding to the tactile sensors, additional modules and LED rings. This way, they can go up to the platform and then downwards to the body through the bigger squared hole, together with the rest of the head cables.

(a) (b)

**Figure 4.14.** Details of the head structural support: (a) Top view, (b) Bottom view.

The platform also has supports to orient the antennas servomotors in the proper direction for emotion transmission ensuring a 360° rotation range and maximum emotional expression. Finally, to support the 4-microphone array at the desired height, a circular piece is threaded to the platform.

#### 4.2.4.2. Front Panel

The front panel is in charge of holding the LCD display and the front LED ring. The display is fixed through a black frame that intends to give the rectangular screen a more complex geometry look. This frame is then assembled into the front cover with a 2 mm Polyvinyl Chloride (PVC) panel in between to protect the screen. A 8-LED ring is embedded in the front of the display frame to keep the optimal distance with the polystyrene ring to diffuse the LED light. Finally, a small piece is used as a lock to prevent the screen from sliding upwards through the frame. Figure 4.15 shows the front panel components.

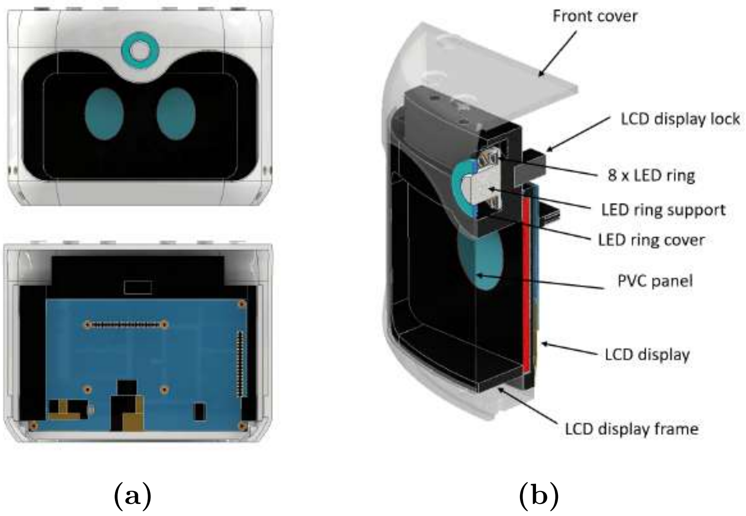



**Figure 4.15.** Details of the head front panel: (a) Front and back views, (b) Cut view.

#### 4.2.4.3. Lateral Panels

Both lateral panels are symmetric and are threaded to the head support platform. They additionally serve as fixation to the head top panel through two threaded embedded inserts and also permit a better fixation of the front and back panels. Each panel consists of a main body and an ear cover. Each of the covers has a **circular silicone tactile sensor** attached. The LED rings of each ear are embedded into the lateral panels at the proper distance from the polystyrene ring for light diffusion. Finally, each panel has three holes for the elastic textile mesh fixation and an embedded male 6-pin port for connecting the additional modules as explained in Section 4.2.6. Figure 4.16 shows the head lateral panels design details.

**(a)** **(b)**

**Figure 4.16.** Details of the head lateral panels: (a) Front and back views, (b) Side view and cut view.

#### 4.2.4.4. Back Panel

The head back panel is attached to the rest of the head components through three bolts, one threaded to the support platform and the other to the two lateral panels. It has two cavities for a 15×24×5 mm bearing on each side for better fixing each antenna base. The panel has been designed with some holes for better air circulation and also has five bolt holes for fixating the elastic textile mesh, as it can be seen in Figure 4.17.

**(a)** **(b)**

**Figure 4.17.** Details of the head back panel: (a) Front view, (b) Back view.

#### 4.2.4.5. Top Panel

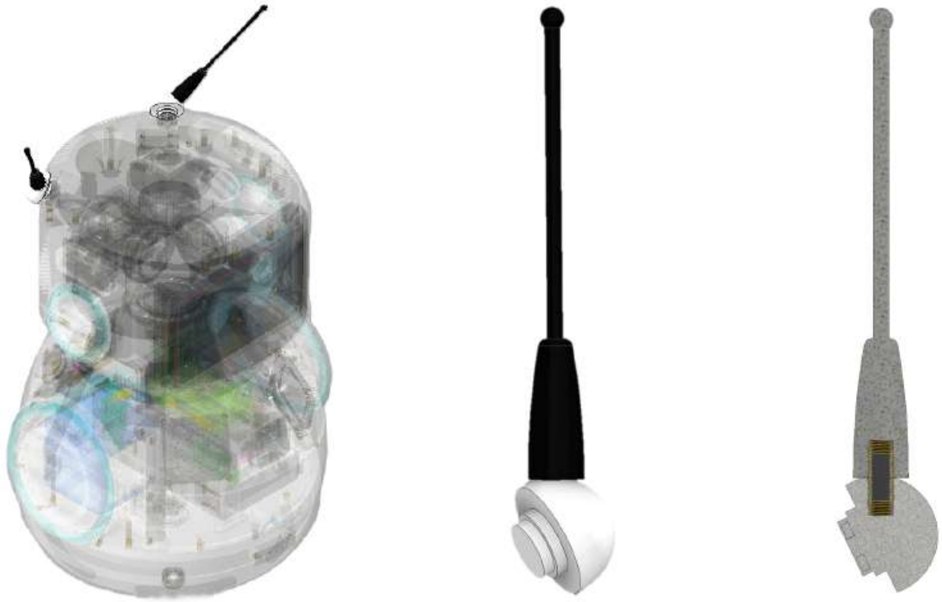
The final component of the head sub-assembly is the top panel, which holds the LDR and the forehead silicone tactile sensor. The top panel is fixed to the lateral panels through two threaded inserts and has several holes for the microphone to properly detect the user's voice. The LDR sensor is supported by a small cover threaded to the bottom of the top panel as it can be seen in Figure 4.18.

**(a)** **(b)**

**Figure 4.18.** Details of the head top panel: (a) Top view, (b) Bottom view.

### 4.2.5. Antennas

The antennas sub-assembly provide **extra emotion transmission capabilities** to the robot and was based on the open-sourced robot Reachy from Pollen Robotics [87]. They have been designed to be **magnetically attached** to the servomotors located inside the head through four neodymium magnets. The base of each antenna is threaded to the antenna tip through two threaded inserts and a stud bolt.

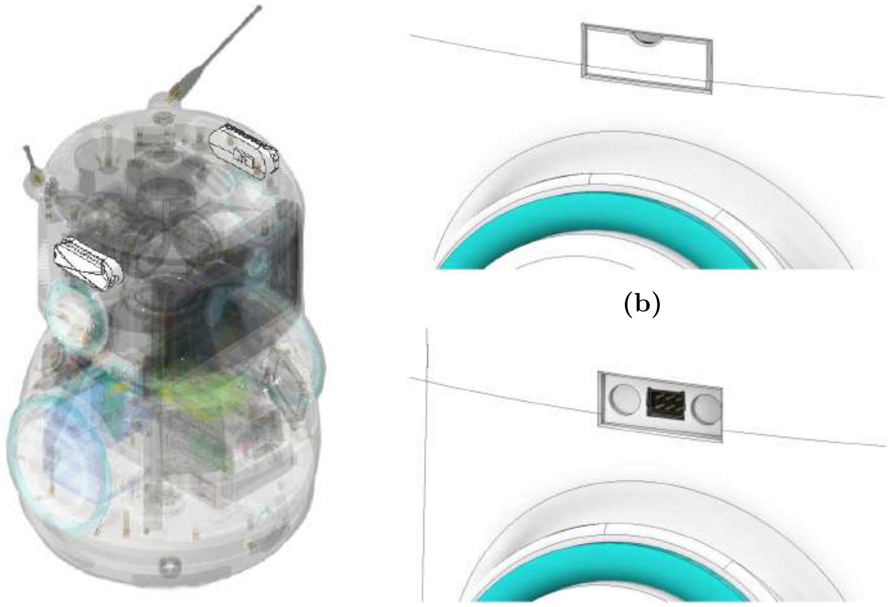


**(a)** **(b)** **(c)**

**Figure 4.19.** Robot antennas sub-assembly: (a) Location in the main assembly, (b) External detail view, (c) Internal detail view.

### 4.2.6. Additional Modules

In order to maximize the flexibility and future capabilities of the hardware, it was decided to include in the design the possibility to attach up to two modules to the robot's head. These modules are connected to the microcontroller in the body of the robot and have a set of connectors to enable multiple functionalities with sensors or actuators. As a proof of concept, three modules were designed: a **flashlight** module, an **air quality and hazardous gas detector** module, and a **NFC** module. These modules are designed to be attached magnetically to the head with a 6-pin male connector. If no modules are connected, the two head 6-pin female connectors are protected with two magnetically attachable covers (through embedded neodymium magnets, two in each cover and two in each head side), as it can be seen in Figure 4.20.



(a) (b) (c)

**Figure 4.20.** Robot modules sub-assembly: (a) Location in the main assembly, (b) Covered port detail, (c) Uncovered port detail.

### 4.2.6.1. Flashlight Module

The flashlight module idea was inspired from Disney Research's robot [44], which incorporates a flashlight in the lateral of its head. It could help to enrich the interaction with the user in environments with low light or to make the robot turn on the flashlight if the lights are turned off for example. Figure 4.21a shows the flashlight module design.

The module design has two main components, the module body and its cover, and is designed to be in the right side of the head. It was ensured the module body adapted to the selected flashlight while offering enough space for the internal electronics. Since the selected flashlight had its own rechargeable lithium-ion battery, it was decided to leave a hole in the module body located at the height of the charge port to enable recharging of the flashlight without needing to disassemble the module. Some holes were added in the upper part for better refrigeration.

(a) (b) (c)

**Figure 4.21.** Additional modules design: (a) Flashlight module, (b) Air quality and hazardous gas detector module, (c) NFC module.

#### 4.2.6.2. Air Quality and Hazardous Gas Detector Module

The air quality and hazardous gas detector module idea was inspired by the artificial nose from Potato, able to detect certain types of gases. Some potential applications of this module could be to monitor air quality and take it as an input for deriving the robot's emotional state or to alert the user in case a dangerous amount of hazardous gas is detected.

The design is similar to the flashlight module, with a main body and its cover. In this case it has been designed to be in the left side of the head. Since the air quality and hazardous gas sensors need to be exposed to the environment air, both the body and the cover of the module were designed with a hole pattern to enable air circulation. This design can be seen in Figure 4.21b.

#### 4.2.6.3. NFC Module

A NFC sensor could offer a variety of potential applications in the social robot, enhancing its interactivity, usability, and overall functionality. Some examples could be the interaction with NFC-tagged materials for **educational settings**, participation in **games and challenges** involving NFC tags to make the interaction more engaging and dynamic, or access to data from medical or fitness wearable devices for **health and wellness monitoring**.

As in the previous cases, it is composed of a main body and a cover. It is designed for the left side of the head and its geometry ensures the user knows where to locate the NFC device with which the interaction is desired. Figure 4.21c shows the module design.

## 4.3. Electrical and Electronic Design

Building on the detailed mechanical framework, the electrical and electronic design phase focuses on the selection, integration, and organization of the robot's critical hardware components. This section outlines the actuators, sensors, control systems, and power supply and communication systems that enable the robot to perform its intended functions.

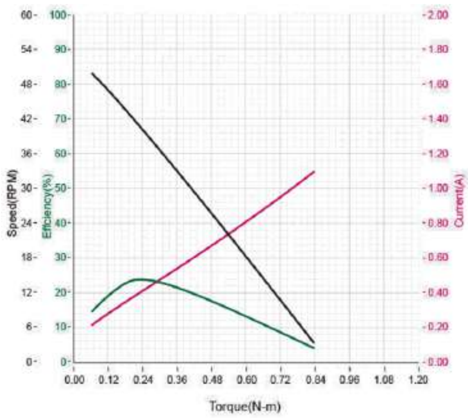
### 4.3.1. Actuators and Output Systems

The actuators and output systems enable the robot to interact effectively with its environment. Key components include motors, speakers, LEDs and the LCD display. These components work together to ensure the robot can perform tasks, communicate, and respond to various scenarios effectively.

#### 4.3.1.1. Motors

Initially, stepper motors were considered for the robot's design due to their precision and ease of control. However, the final decision was to use "smart" motors, specifically those manufactured by Dynamixel, which offer significant advantages over traditional stepper motors.

**Dynamixel motors** provide advanced features such as precise position, speed, and torque control. Moreover, they offer feedback on parameters like position, load, and temperature, which is particularly useful for monitoring the robot's performance. It also offers a shield with the motor drivers, further easing the hardware implementation and control.




(a)

(b)

**Figure 4.22.** Motors: (a) Dynamixel XL-430-W250-T current versus torque curve, (b) Dynamixel XL-320 (left) and XL-430-W250-T (right) models [92][93].

To determine the appropriate motors for the project, Autodesk Inventor was used to determine some of the robot's components principal axis inertias. For example, with the inertia of the robot head and the desired angular acceleration, the required neck yaw motor torque could be determined. The resulting torque values were then compared against the **torque versus current diagrams** provided in the motor datasheets such as the one shown in Figure 4.22a. This step was crucial to ensure that the total torque demands would not exceed the battery capabilities (around 4 or 5 A), especially considering the use of Li-ion battery, which has lower current drain capacity compared to Li-Po batteries and that it must also be able to provide current to other elements in the robot.

Given these constraints, **four Dynamixel XL-430** [93] were selected for the robot's rotary base and neck mechanism, able to stall torque of up to 1.5 Nm at 12 V. Additionally, **two** smaller **Dynamixel XL-320** motors [92] were chosen for the robot's antenna mechanisms. These motors are lightweight and compact, with a stall torque of 0.39 Nm at 7.4 V, which is sufficient for the antenna movements. Figure 4.22b shows the two chosen motors respectively. A notable feature of the XL-320 motors is their ability to provide torque feedback, which can be utilized as sensors. This capability allows the robot to detect when its antennas are touched, adding and interactive element to the design.

For the pitch and roll motors in the neck mechanism, the calculations were more complex. Due to the initial mechanism's multiple loops, simulations in Inventor were attempted but proved time-consuming. As a result, a simplified prototype, shown in Figure 4.23 was printed to test whether the motors could generate the required torque, qualitatively confirming that the motors could effectively handle the task.

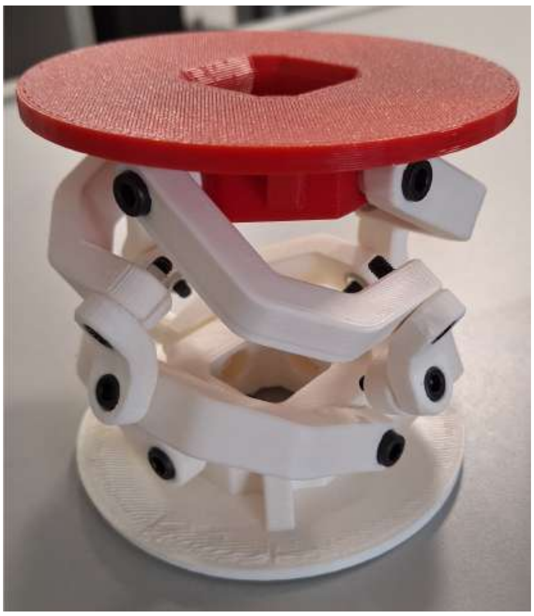


**Figure 4.23.** Testing initial neck mechanism prototype.

#### 4.3.1.2. Speakers

For having a robust solution for the robot's audio output needs, two Tectonic speakers [94], paired with the 2×5 W AMP Click audio amplifier [95] were selected. These speakers provide a full-range audio response from 100 Hz to 20 kHz, ensuring clear and detailed sound. The compact size and relatively low power requirements make these speakers suitable for its integration in the robot. With respect to the amplifier, it ensures efficient power usage and high-quality sound amplification. Its filter-less operation and selectable gain settings allow for tailored audio output, making it adaptable to different use cases within the robot. Both the speakers and the audio amplifier can be seen in Figures 4.24a and 4.24b respectively.


**(a)** **(b)**

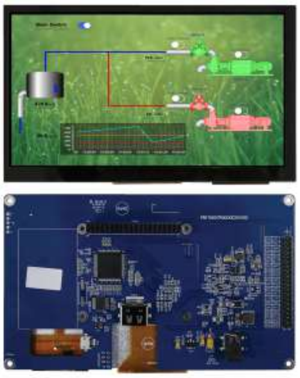
**Figure 4.24.** Audio subsystem: (a) Speakers [94], (b) Audio amplifier [95].

#### 4.3.1.3. LCD Screen

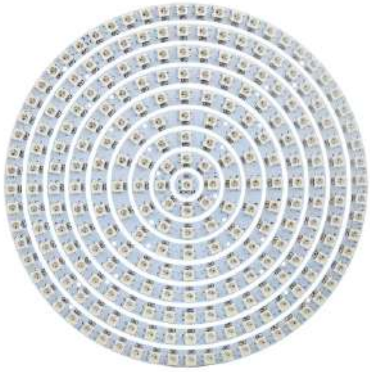
The 7.0" LCD screen from Midas Displays [96] is a good choice for the robot's face due to its high resolution of 1024×600 pixels, offering clear and detailed visuals. Its LED backlight ensures good visibility in different lighting conditions, and the HDMI interface simplifies integration with the robot's hardware. The robot's display can be seen in Figure 4.25a.

#### 4.3.1.4. LEDs

There exist different LED circular ring sizes. Each LED is individually addressable, allowing for complex lighting patterns with just a single microcontroller pin. The slight design, powered by 5 V, integrates seamlessly into the robot. The six rings used in the robot are: one 1-LED ring for the heartbeat indicator, one 8-LED ring for the forehead, two 16-LED rings for the ears and two 40-LED rings for the body. The rings can be seen in Figure 4.25b.



(a)



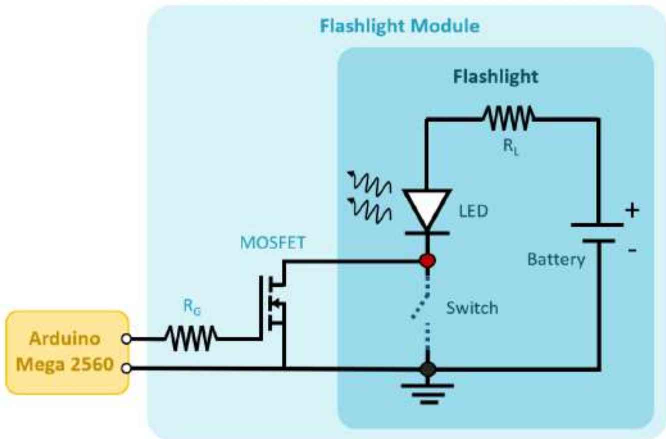
(b)

**Figure 4.25.** Light actuators: (a) LCD display [96], (b) LED rings.

#### 4.3.1.5. Flashlight

The flashlight selected for its integration into the robot's flashlight module has been chosen to be the Nitecore Tube 2.0 [97], which can be seen in Figure 4.26a. This decision was based mainly on its ease of modification. One of the key features that make this flashlight a good choice is its simple single-switch operation, which can be easily adapted by replacing the button with a Metal-Oxide Semiconductor Field-Effect Transistor (MOSFET). This modification will allow the flashlight to be controlled digitally through an Arduino GPIO port, enabling the robot to turn the light on and off programmatically. Additionally, the flashlight's two brightness levels and built-in rechargeable 125 mAh 3.7 V battery make it a versatile and energy-efficient option.


(a)




(b)

**Figure 4.26.** Flashlight module: (a) Nitecore Tube 2.0 flashlight [97], (b) Flashlight module electronic scheme.

The flashlight has an internal circuit that enables it to work in three states depending on how many times the button is clicked: low and high light intensity and turned off. The circuit can be simplified to better understand it to be the circuit showed in Figure

4.26b. By removing the button or switch, two cables are left unconnected, these two cables will be connected to the drain and the source of the MOSFET respectively. The MOSFET's gate will be connected to an Arduino GPIO port through a gate resistor, $R_G$, to control the flashlight from the Arduino. This resistor is chosen to be 1 kΩ to restrict the maximum current drained from the GPIO Arduino port at 5 V. The chosen MOSFET is the IRL540PBF, which can work in the saturation region with 5 V and has more than enough continuous drain current to deal with the 0.1 A maximum current drained by the flashlight LED in maximum light intensity mode. The three flashlight modes would be controlled by sending one or two pulses to the MOSFET's gate.

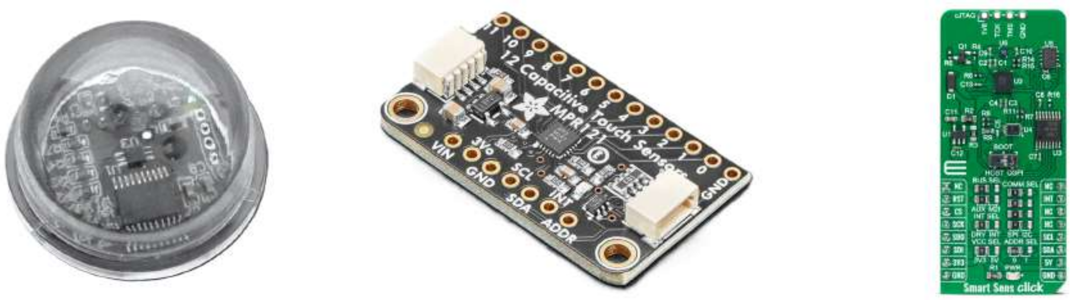
## 4.3.2. Sensors and Data Acquisition

The sensors and data acquisition systems are crucial for the robot's ability to perceive and interact with its environment. This section details the various sensors integrated into the robot, including environmental sensors that allow the robot to monitor and respond to external conditions, and feedback sensors that provide real-time data on the robot's internal states.

### 4.3.2.1. Environmental Sensors

#### LDR Sensor

A LDR sensor is a type of resistor whose resistance decreases with increasing incident light intensity. The DFRobot Ambient Light Sensor (SKU: SEN0390) was selected for the robot due to its high accuracy, wide detection range (0 - 200,000 lux), and ability to simulate the human eye's perception of light [98]. Its compact design, combined with I2C communication, allows for easy integration and reliable light sensing, making it ideal for the robot's environmental interaction needs. Figure 4.27a shows the selected sensor.




(a) (b) (c)

**Figure 4.27.** Environmental sensors: (a) DFRobot LDR sensor [98], (b) Adafruit MPR121 [99], (c) Mikroe IMU [100].

### Tactile Sensors

The Adafruit capacitive-based touch sensor MPR121 [99] was chosen for its ability to handle up to 12 touch-sensitive electrodes, making it ideal for detecting multiple interactions on the robot's surface. Its I2C interface ensures easy integration with Arduino, and features like auto-calibration and configurable sensitivity enhance its reliability. The tactile electrodes are designed to be made out of silicone, a material chosen for its flexibility, durability, and skin-like texture, enhancing the tactile experience for users. While alternatives like resistive and optical touch sensors were considered, they either lacked multi-touch capabilities or required more complex interfacing, making the MPR121 the most efficient choice for the project. The selected device can be seen in Figure 4.27b.

### Inertial Measurement Unit (IMU)

An IMU is able to measure a device's accelerations, angular rates, and sometimes magnetic field surrounding the body, enabling to determine its orientation and movement in the 3D space. In the social robot it could be used to reorient itself or for example to detect when the robot is lifted from the table. The Smart Sens Click module [100] was selected for the robot primarily due to its integration of a high-performance 6-DOF IMU, which includes an accelerometer and gyroscope, combined with a magnetometer, all within a compact and low-power package.

The choice of a Click module, specifically, provides several advantages. Click modules are designed for ease of integration with existing systems, offering a standardized form factor and pinout that simplifies the hardware design process. This reduces the time needed to implement and troubleshoot the sensor integration. Furthermore, the inclusion of a programmable 32-bit microcontroller unit withing the sensor offloads sensor data processing tasks from the robot's main Central Processing Unit (CPU). Figure 4.27c shows the selected IMU.

### Microphone

The ReSpeaker Mic Array v2.0 [101] was selected for the social robot due to its advanced capabilities in voice recognition and audio processing. This microphone array features a chipset which provides enhanced digital signal processing capabilities, including acoustic echo cancellation, beamforming, and noise suppression. Its four high-performance digital microphones provide far-field voice capture, enabling the robot to recognize voices and their incoming direction, useful in dynamic environments where users may not be directly in front of the robot. The microphone array can be seen in Figure 4.28a.

(a) (b) (c)

**Figure 4.28.** Environmental sensors: (a) ReSpeaker Mic Array v2.0 [101], (b) Intel RealSense D405 Camera [102], (c) Leap Motion Controller [103].

### Intel RealSense D405 Camera

The Intel RealSense D405 [102] is an ideal choice for the social robot due to its specialized capabilities as an RGB-D camera, which captures both color (RGB) and depth (D) data for each pixel. This dual-functionality allows the camera to create highly detailed 3D maps of the robot's environment. The D405's sub-millimeter accuracy, operating within a range of 7 to 50 cm, is particularly valuable for close-range interactions. Additionally, its compact and lightweight design facilitates easy integration into the robot. The selected camera can be seen in Figure 4.28b.

### Leap Motion Controller

The Leap Motion Controller [103] is an ideal addition to the social robot, enhancing user interaction through precise hand-tracking capabilities. Its ability to capture detailed hand movements within a 3D interactive zone of up to 60 cm allows for natural, touchless interaction, improving the robot's ability to understand and respond to user gestures effectively. This functionality opens up a wide range of applications, such as interactive educational tools or sign language interaction. Figure 4.28c shows the selected device.

### Air Quality Sensor

The Gravity ENS160 Air Quality [104] is ideal for a social robot designed for indoor environments. It uses advanced technology to accurately measure key air quality indicators like total volatile organic compounds (TVOC), equivalent $CO_2$, and Air Quality Index (AQI). With a fast response time and automatic baseline correction, it ensures reliable, long-term data, allowing the robot to effectively monitor and maintain a healthy indoor environment for users. Its compatibility with I2C interfaces and simple integration make it a practical choice for enhancing the robot's functionality.


(a) (b) (c)

**Figure 4.29.** Environmental sensors: (a) Gravity ENS160 Air Quality [104], (b) Fermion MEMS Gas Sensor MiCS-5524 [105], (c) NFC Click module [106].

### Hazardous Gas Sensor

For improving the indoor environment robot's monitoring capabilities, the Fermion MEMS Gas Sensor MiCS-5524 was selected [105]. This sensor is versatile, supporting various harmful or dangerous gas detections (CO, $CH_4$, $H_2$, and $NH_3$ among others), making it ideal for enhancing the safety capabilities of the robot. Additionally, its low power consumption and analog output facilitate easy integration with the robot's existing hardware. Figure 4.29b shows the selected sensor.

### NFC Sensor

The NFC Click module from Mikroe [106] was selected for its robust capabilities in enabling contactless communication, essential for modern interactive applications. This sensor is particularly valuable in the context of a social robot for its versatility. Its ability to operate in multiple modes, including reader/writer, card emulation, and peer-to-peer communication, makes it ideal for enabling seamless interactions between the robot and other NFC-enabled devices, such as smartphones or smart wearables. Its I2C interface ensures easy integration into the robot's existing hardware and software systems. The sensor can be seen in Figure 4.29c.

## 4.3.2.2. Feedback and Monitoring Sensors

### Wattmeter

The Gravity I2C Digital Wattmeter [107] was selected for monitoring the voltage and current drained from the network (since on battery power the battery already integrates a management system) in the social robot due to its good precision and resolution, capable of measuring up to 26 V and 8 A with minimal error. This compact module provides accurate real-time monitoring, which is crucial for efficient energy management and extending battery life in the robot. Its easy integration with Arduino makes it ideal for ensuring the robot's power system operates reliably and efficiently. Figure 4.30a shows the selected sensor.

(a) (b) (c)

**Figure 4.30.** Feedback and monitoring sensors: (a) Wattmeter [107], (b) RTC [108], (c) Buck converter [109].

### Real-Time Clock (RTC)

The RTC 16 Click [108] is an ideal choice for the robot's time-keeping needs due to its accurate time management and low power consumption. This module provides precise time and calendar data via an I2C interface, ensuring reliable operation even during power outages thanks to its battery backup capability. Its ability to generate interrupts for alarms and other events makes it useful for scheduling tasks and managing power efficiently within the robot. This sensor makes the robot more versatile and enhances the robot capabilities in time-sensitive applications. The selected sensor can be seen in Figure 4.30b.

### Buck Converter

In order to power the servomotors at 8 V efficiently, the Buck 6 Click module [109] was selected as the ideal solution. This advanced DC-DC step-down converter offers a wide input voltage range and provides a digitally adjustable output, ensuring precise control over the motor's power supply. Its robust features, including overcurrent and overtemperature protection, ensure safe operation under varying load conditions. Figure 4.30c shows the selected buck converter click module.

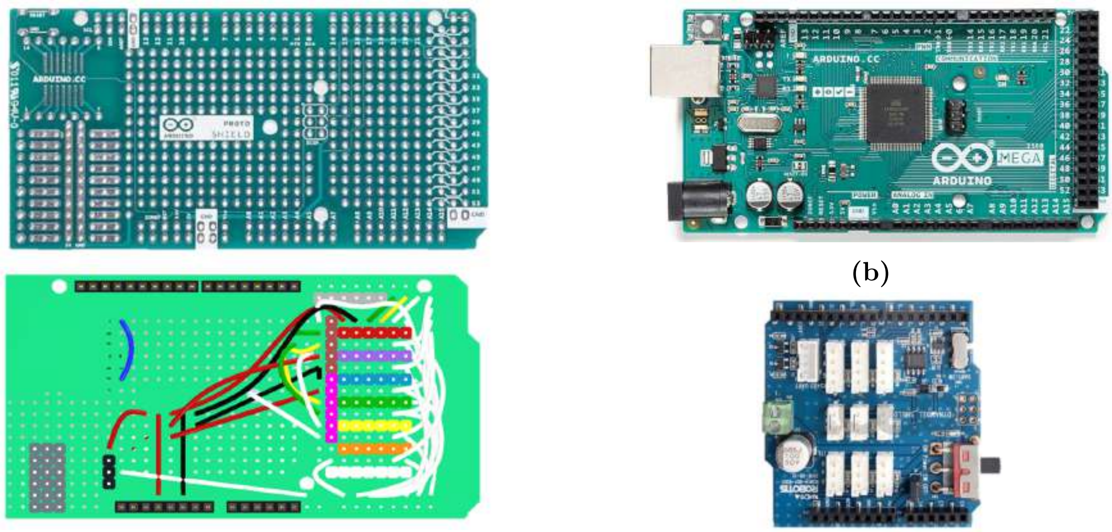
## 4.3.3. Control Systems

The control systems of the robot form the central nervous system that integrates all the hardware components, ensuring seamless communication and coordinated functionality. At the heart of this system is the Arduino Mega 2560 microcontroller, which is tasked with reading sensor measurements and executing actuator commands. These actions are based on higher-level directives from the NVIDIA Jetson TX2i, which handles more complex software tasks such as emotion detection, speech analysis, and dialog management. This architecture ensures that the robot can process sensory inputs and react in real-time, making its interactions more lifelike and responsive.

#### 4.3.3.1. Arduino Mega 2560

The Arduino Mega 2560 [110], shown in Figure 4.31b, is a widely used microcontroller board based on the ATmega2560 chip, known for its extensive I/O capabilities and robust performance in prototyping and development projects. It was chosen for this project due to its high number of digital and analog pins, which are crucial for managing the numerous connections required in the development of a complex social robot. This Arduino had already been acquired and was thought to be sufficient for the first prototype.

To streamline wiring and ensure secure connections, the Arduino Mega Proto Shield [111] was employed, with **layouts meticulously designed in Autodesk Inventor using a color-coded scheme** for each device and cable, as it can be seen in Figure 4.31a. This visual planning confirmed that all components fit within the board's limited space, though a multiplexer was considered to expand capabilities if needed. The manual wiring was preferred to a custom Printed Circuit Board (PCB) because the prototyping phase requires **flexibility** to make quick adjustments as the design evolves, and it is cheaper and time-efficient in the short-term.




(a) (b) (c)

**Figure 4.31.** Microcontroller sub-assembly: (a) Arduino Mega Proto Shield [111] and Inventor connections planning, (b) Arduino Mega 2560 [110] (c) Dynamixel Shield [112].

The Arduino Mega 2560 is typically programmed via its built-in UART interface. For integration with the Jetson TX2i, a USB-to-Transisitor-Transistor Logic (TTL) serial

UART converter was planned to enable direct programming from the Jetson, streamlining development. However, this integration was not implemented due to time constraints.

For motor control, the **Dynamixel shield** [112] shown in Figure 4.31c was used, simplifying the connection to Dynamixel servomotors. This shield has ports connections for several motors and they are connected in series so the hardware implementation is simpler. Dynamixel, in a similar way to the manufacturers of the rest of electronic components, provides a **library** that further facilitates straightforward motor control.

#### 4.3.3.2. NVIDIA Jetson TX2i

The NVIDIA Jetson TX2i [113] is a compact, high-performance AI computing module, ideal for the development of robots that require real-time data processing and robust, energy-efficient operation. Its powerful CPU and Graphics Processing Unit (GPU) enable advanced AI tasks such as facial recognition or NLP. The module's integrated heatsink, which can be seen in 4.32a ensures it stays cool even during intensive operations.

The inclusion of a 1 TB SSD provides ample storage for AI models, user data, and multimedia content, allowing the robot to store and access information quickly, enhancing its responsiveness and learning capabilities. The disk can be connected to the Jetson TX2i through the expansion board shown in Figure 4.32b.

Additionally, equipping the Jetson TX2i with the **Wi-Fi antenna** [114] shown in Figure 4.32c allows the robot to connect seamlessly to networks for data exchange, software updates, and remote control. This connectivity enables real-time communication and integration with cloud services, increasing the robot's potential future applications.


**(a)** **(b)** **(c)**

**Figure 4.32.** Processing unit sub-assembly: (a) NVIDIA Jetson TX2i and its heatsink [113], (b) SSD Disk and its expansion board for NVIDIA Jetson TX2 [115], (c) WiFi omnidirectional antenna [114].

### 4.3.4. Power Supply and Communications

The robot is designed to operate either plugged into an external power source or on battery power, selectable through a mode switch located on the ports panel. This flexibility allows the robot to function in various scenarios.

The primary power source is a **Lithium-ion** 4S4P 18650 **14.4 V 10.4 Ah** battery [116], chosen for its high energy density, long life cycle, and integrated battery management system, which protects against overcharge, over-discharge, and short circuits. The selected battery can be seen in Figure 4.33a. Safety is a priority, and that is why a 4 A fuse was installed in the ports panel to quickly cut off power in case of any malfunction or hazard.

**(a)** **(b)**

**Figure 4.33.** Power supply: (a) Lithium-ion 4S4P 18650 battery [116], (b) USB 3.0 7-Port Hub [117].

To manage connectivity and peripheral devices, a USB hub [117] is integrated, allowing multiple components to connect to the robot's processing units. Figure 4.33b shows the selected 7-port hub. Once the power button from the ports panel is activated, the Arduino Mega 2560, audio amplifier, USB hub, and the Dynamixel shield's buck converter are powered by 12 V (or 14.4 V when battery-powered). The buck converter steps down the voltage to 8 V for the Dynamixel shield, as 8 V falls withing the **operating range for the two selected motor models**.

The Arduino Mega 2560 then provides 5 V to power the Jetson TX2i, the LCD display, and other connected devices. The USB hub supplies 5 V to the SSD, D405 camera, Leap Motion Controller, microphone array, and serial converter PCB. Additionally, the NFC sensor requires a 3.3 V input, which will be provided by a separate buck converter. The overall power supply scheme is illustrated in Figure 4.34. Note that the dashed boxes indicate components planned in the design but not yet implemented due to time constraints.

The communication connections for the entire system have been carefully planned, as shown in Figure 4.35. The two USB-C ports are connected to the USB hub, while the Ethernet port is linked directly to the Jetson TX2i. The Jetson communicates with the

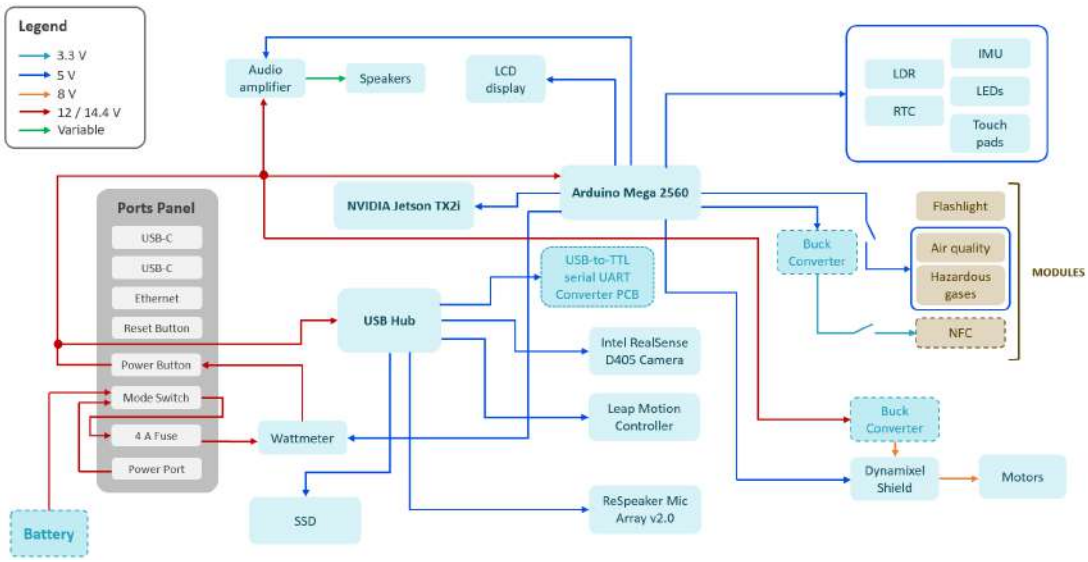



**Figure 4.34.** Overall designed power supply scheme.

Arduino Mega via the UART protocol and outputs the robot's facial displays through an HDMI connection to the LCD display. The Arduino Mega manages most of the robot's sensors and actuators using the I2C protocol, where it acts as the master, with the sensors and actuators as slave nodes. Controlling the flashlight is straightforward, requiring only one GPIO digital port to toggle its various modes.

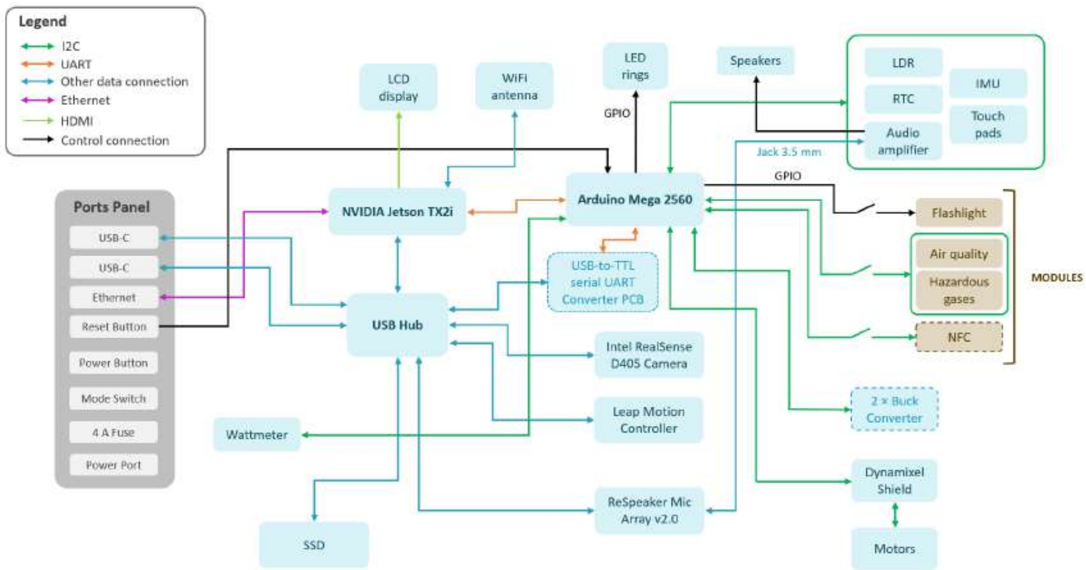



**Figure 4.35.** Overall designed communications scheme.

Due to the prototype nature of the project, detailed documentation on the specific connections of the protoshield pins is not yet available. The arrangement design in Figure 4.31b, created in Autodesk Inventor, provides an overview of the current setup, where each color array corresponds to a distinct I2C device, all powered with 5 V, sharing a common ground, and connected to the SCL-SDA bus. At this stage, the focus has been on ensuring functional power and communication connections. However, as the protoshield has limited space and requires constant adjustment, a detailed pin connection layout is subject to change through further testing and iterations. The development of a detailed electronic schematic, which includes all wiring and component connections, is planned as a priority for future work. This will also serve as a foundational step towards developing a custom PCB, which will resolve space constraints and facilitate more efficient wiring.

## 4.4. Emotional Faces Design

In the design of the robot's emotional faces, **minimalism** played a central role, aligning with the overarching aesthetic principles of the project. This minimalist approach was pivotal in deciding the specific features used to express emotions.

Several alternatives were explored during the conceptualization phase. One option included a full facial display, utilizing eyes, eyebrows, and a mouth to offer a broad range of expressions. Ultimately, the decision was made to use only the **eyes** as elements of facial expression. This choice was driven by several factors:

- **Simplicity:** Using only the eyes simplifies the design and development of face animations.
- **Effectiveness:** Research suggests that the eyes alone can convey a wide spectrum of emotions effectively [118]. They are often regarded as the most expressive part of the face, capable of demonstrating joy, sadness, anger, fear, and surprise with subtle changes in appearance.
- **User interaction:** Minimalist design can enhance user interaction by focusing attention on a specific area, making it easier for users to read and understand the robot's responses without overwhelming them with too many details.

**Color psychology** was another crucial factor in the design of the robot's emotional faces. Different colors were chosen to represent different emotions, enhancing the expressive capability of the eyes without the need for additional facial features [40]. The set of designed emotions were based on **Plutchik's wheel** of emotions model, since it is the one used in Potato. The static face design iteration process was done in Inventor to ensure proper integration with the rest of the robot. With this approach, the full emotions could be designed, including **LEDs color and body position**. Figure 4.36 shows the designed set of emotions based on Plutchik's wheel.

It can be observed how certain emotions such as fear make use of the head and antennas position to better transmit the desired feeling. However, static emotions are less effective than **dynamic** ones, that is why face animations were designed with **Piskel** for four

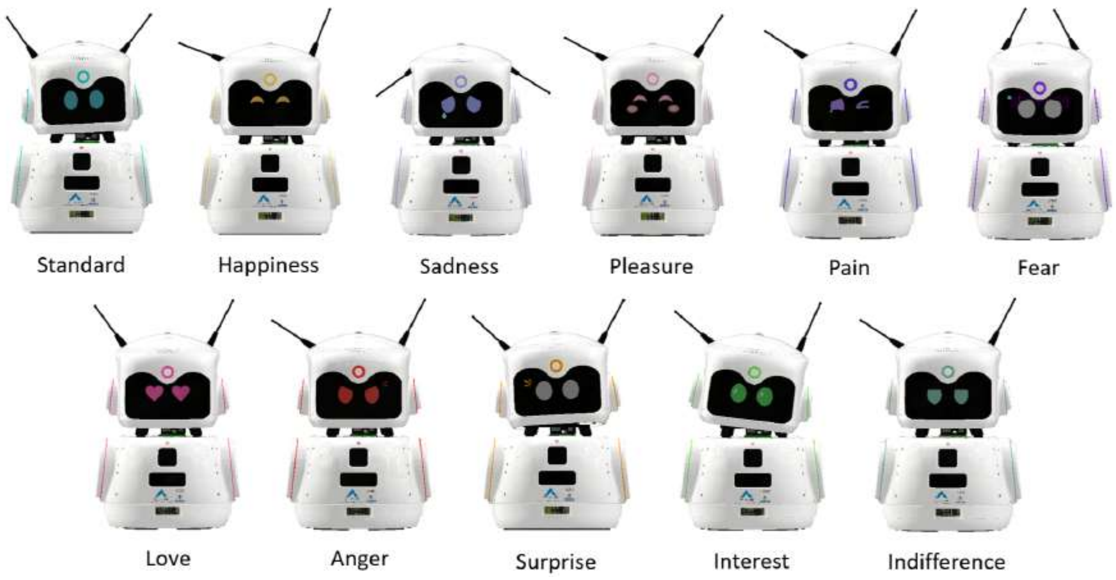



**Figure 4.36.** Set of designed robot emotions.

different emotional states to serve as a demo of the robot future capabilities. The face designs for each of these emotional states: normal, happiness, fear and love; can be seen in Figure 4.37.

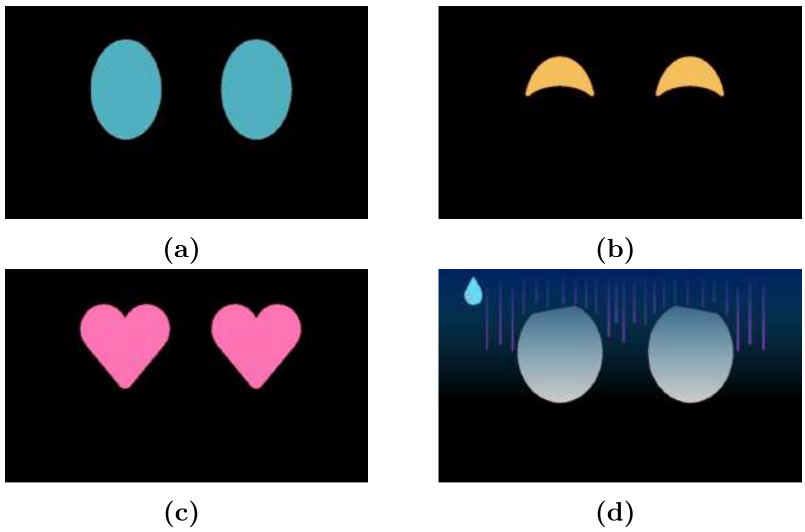



**Figure 4.37.** 1024×600 demo face designs: (a) Normal, (b) Happy, (c) Loving, (d) Scared.

Different spritesheets were designed, both for the emotions and for the **transitions between emotions** to showcase a smoother and more natural mood transition. Figure 4.38 shows all the spritesheets together, being each row corresponding to one animation of 32 frames.

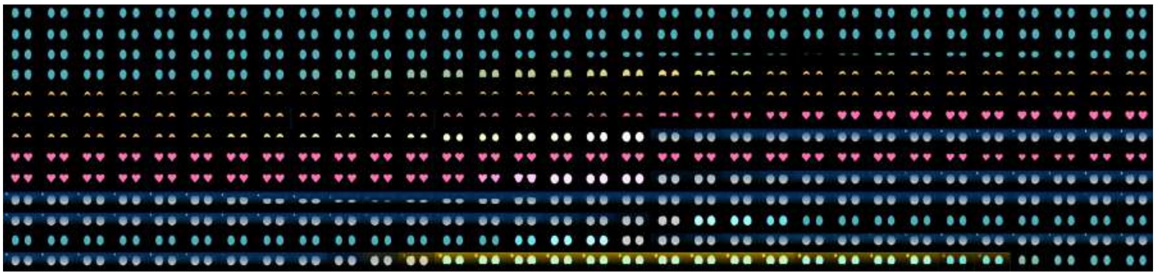


**Figure 4.38.** 13×32 spritesheet including 13 animations corresponding to four emotions and their corresponding transitions and some demo extra animations.

Chapter 5

# Robot Manufacturing

This chapter details the manufacturing process that brought the robot from design to reality. It covers material selection, component sourcing, fabrication techniques like 3D printing and laser cutting, and the mechanical and electrical assembly. The chapter also addresses challenges faced and the modifications made to optimize the final product.

## 5.1. Materials and Components

The choice of materials and components is crucial in the manufacturing process, as it directly impacts the robot's performance, durability, and overall functionality. This section outlines the materials selected for the robot's construction and additionally covers the sourcing and procurement strategies employed to obtain the necessary components, ensuring that the project stayed within budget and met all design specifications.

### 5.1.1. Selection of Materials

The materials selected for the robot's construction were chosen based on their specific properties, ensuring that each component meets the necessary durability, flexibility, and functionality requirements. Below is an overview of the materials used and the justification for their selection:

- **PETG:** Most of the robot's components were 3D printed using PETG, a material that combines strength and flexibility, making it ideal for durable and functional parts. PETG's resistance to warping and superior durability and temperature resistance compared to PLA made it the preferred choice for the main structure, where both mechanical robustness and ease of printing were crucial.

**Figure 5.1.** Robot materials selection from RS Iberia and Amazon: (a) PETG 1.75 mm filament, (b) ABS 1.75 mm filament, (c) 2 mm transparent PVC panel, (d) 3 mm polystyrene panel, (e) 3 mm silicone sheet, (f) Anti-slip foam adhesives, (g) Nylon elastic textile mesh.

- **ABS:** It was chosen for the main neck mechanism due to its durability, impact resistance, and ability to withstand frequent movement and support the head.
- **Polystyrene:** A 3 mm polystyrene panel was selected for diffusing the LED light proceeding from the LED rings. This material ensures uniform light distribution, enhancing the visual impact of the robot.
- **Silicone:** It was chosen for the tactile pads due to its flexibility and soft texture. Silicone's durability and ability to withstand repeated use make it ideal for components that will experience frequent human interaction.
- **Anti-slip foam adhesives:** The lower part of the robot features anti-slip foam adhesives, which provide stability and prevent unwanted movement on smooth surfaces.
- **Nylon elastic textile mesh:** Used to cover the neck mechanism, providing both aesthetic appeal and safety with its flexibility and durability while withstanding repeated movement.
- **PVC panel:** For the robot's head, a 2 mm PVC panel was selected due to its flexibility to achieve a visually appealing finish, particularly important in the head where aesthetics is crucial.

### 5.1.2. Sourcing and Procurement

The sourcing and procurement was critical to the timely and cost-effective completion of the robot, ensuring that all components were acquired efficiently and within budget.

- **Component Selection:** Components were selected based on availability, cost, and quality, with a focus on sourcing from reliable suppliers such as RS Iberia, Amazon Business and Mouser. Preference was given to components that offered the best balance of performance and price, while also ensuring they met the technical requirements of the design.
- **Supply Chain Management:** Components were ordered well in advance to ensure sufficient time for manufacturing. Most of the components were purchased at the beginning of the project, with additional smaller orders made as needed for extra components as the project progressed. This proactive approach helped to avoid delays and ensure that all necessary materials were available when required.
- **Budget Considerations:** The procurement process was closely tied to the project's budget constraints. Regular cost reviews were conducted to ensure that expenditure remained within the allocated budget, without compromising the quality or functionality of the robot.

## 5.2. Manufacturing Process

After building the initial SPM neck mechanism prototype to qualitatively test the required torques to assist the motors selection process, the definite version of the SPM neck mechanism was the first thing to build.

### 5.2.1. SPM Mechanism, Support Structure and Head Panels

The pieces of each of the four arms were printed and then the whole mechanism subassembly was built inserting the roller bearings in the pieces. Figure 5.2 shows the printed SPM mechanism.

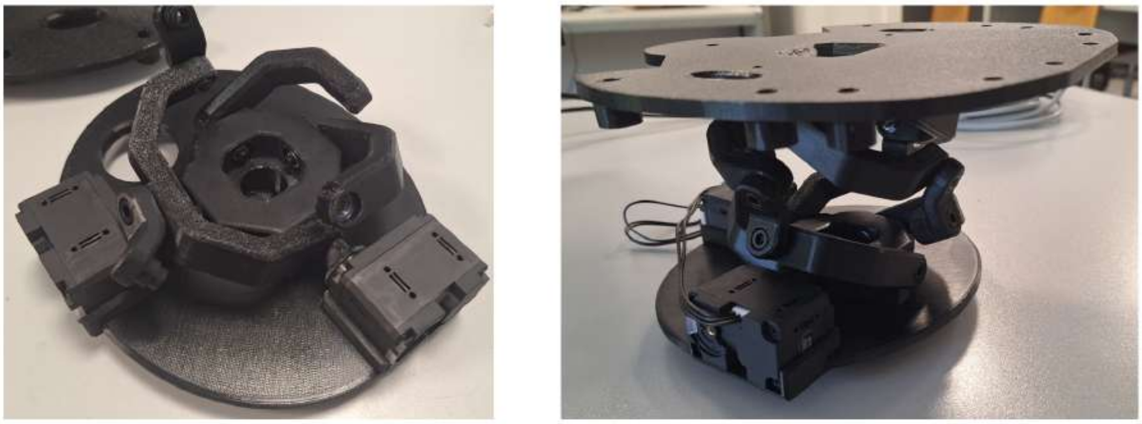
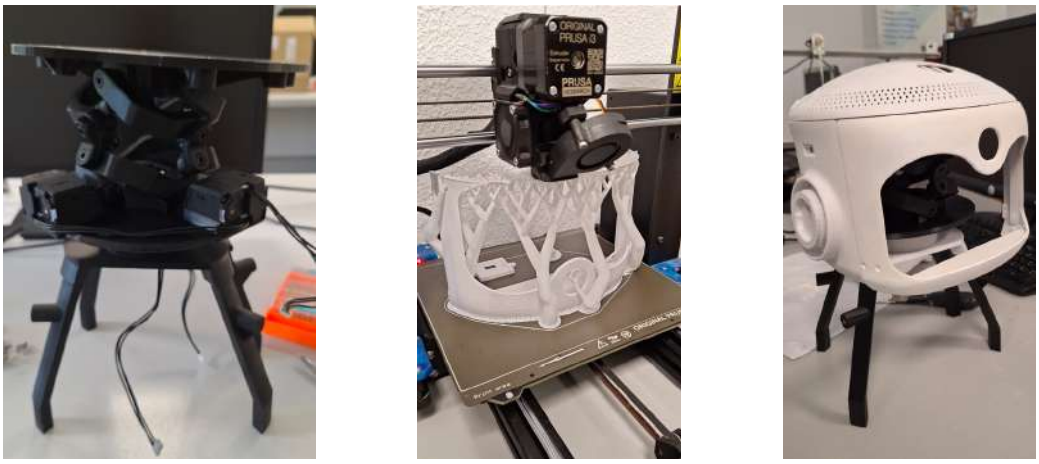


**Figure 5.2.** 3D printed 2-DOF SPM neck mechanism.

Next, the support structure and the head external panels, antennas and ports panel were printed. The structural elements were printed with black PETG, while the external panels were printed in white PETG. The 3D printing process was monitored through the Prusa Link tool. Once the support structure was printed, it was assembled with the neck mechanism as it can be seen in Figure 5.3a.




(a) (b) (c)

**Figure 5.3.** 3D printed parts: (a) Support assembled with the neck mechanism, (b) Front panel during printing process, (c) Head external panels.

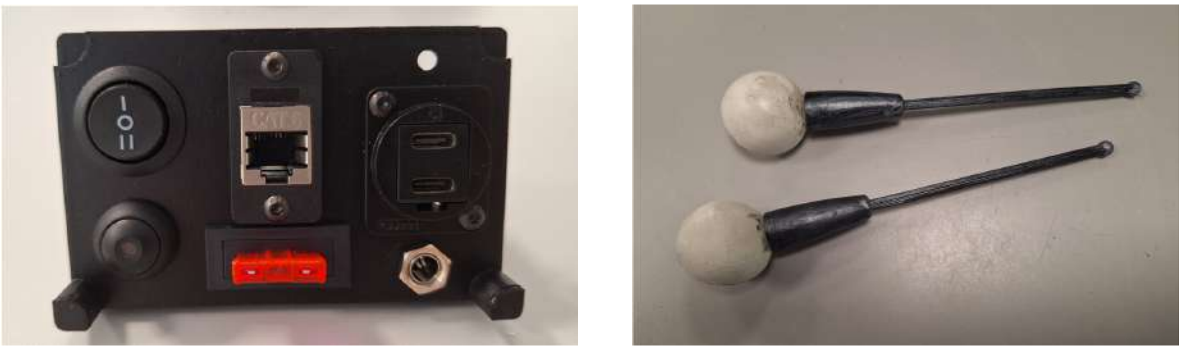
The next step was to **post-process** the external the components to improve their appearance. To achieve this, the pieces were first gradually sanded to smooth out the surfaces and minimize the visible layer lines from 3D printing. Putty was then applied to fill in any remaining imperfections and further reduce the appearance of defects, as it can be seen in Figure 5.4a.

Once the surfaces were adequately prepared, the pieces were primed as it can be seen in Figure 5.4b to create an even better base for the final paint finish. Finally, a couple of layers of paint were applied to achieve the desired aesthetic and ensure a smooth, professional look, as shown in Figure 5.4c. In the end it was decided to paint the robot with a dirt wash style to look it make older and give it a more characteristic style.

(a) (b) (c)

**Figure 5.4.** Post-processing steps: (a) Putty application on the front and top head panels, (b) Priming process, (c) Painting process.

After the ports panel piece was printed and painted, the different switches, ports and buttons were assembled onto the panel as it can be seen in Figure 5.5a. The antennas were also assembled by threading the spherical pieces with the antennas' bases.



**(a)** **(b)**

**Figure 5.5.** 3D-printed parts: (a) Ports panel, (b) Antennas.

### 5.2.2. Arduino Proto Shield Connections

To test the designed SPM neck mechanism with the head load, the next step was to **manually wire** the protoshield as planned in the Inventor electronic layout. This required meticulous work to achieve a compact and organized cable arrangement. Figure 5.6 shows the protoshield with the connections that allow to use the Dynamixel shield mounted on the Arduino Mega. The cables hanging from one side are power terminals intended for connection to the ports panel. Additionally male pins were added to the protoshield to facilitate easy plugging and unplugging of the connected sensors and actuators.

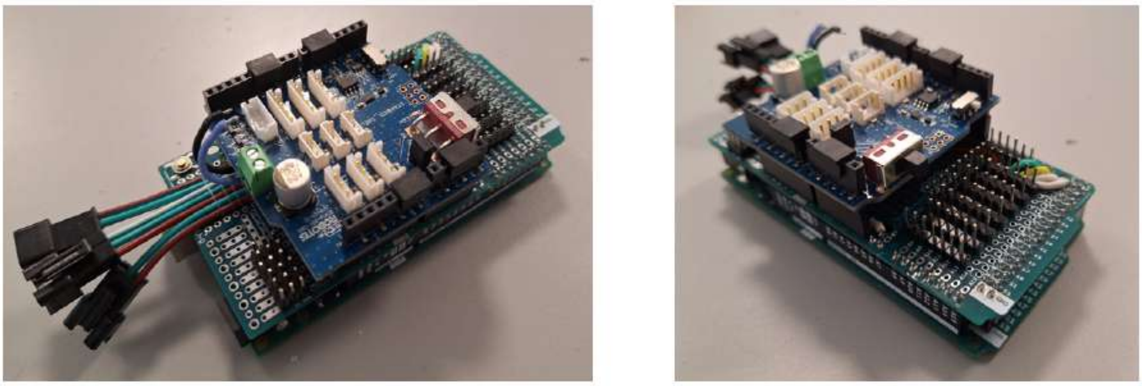
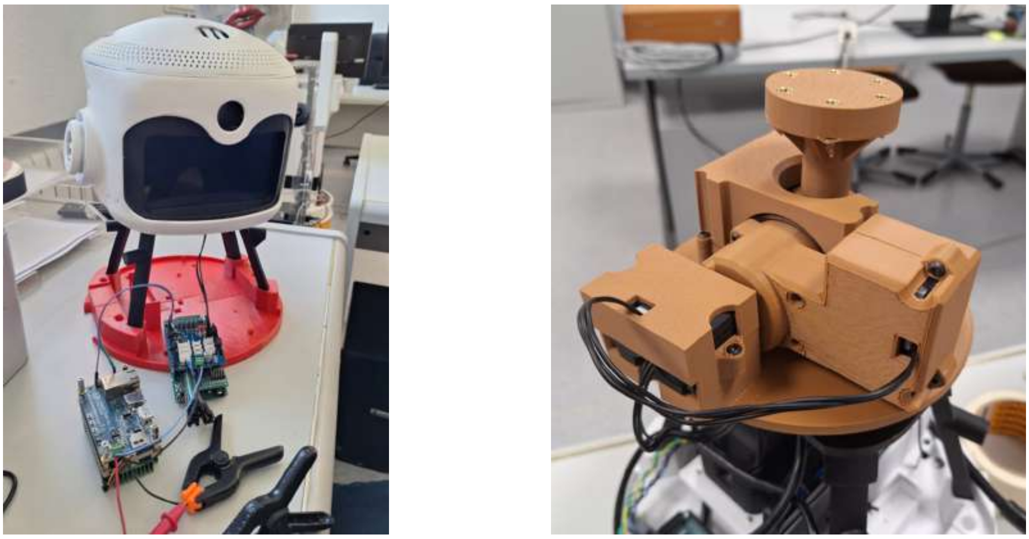


**Figure 5.6.** Arduino with mounted partially connected protoshield and Dynamixel board.

### 5.2.3. Spherical Gear Mechanism

Due to a shortage of PETG filament caused by some print errors and iterative design changes, PLA was used to provisionally to print a base for testing the neck mechanism moving the mounted head, as it can be seen in Figure 5.7a. During testing, it was observed that the mechanism **could not lift the head** (adjust the pitch angle) with the motor at its maximum designed position. This led to the conclusion that the issue was not with the motors, but with the mechanism itself. If manufactured from a more rigid material, such as aluminum, the mechanism would have more effectively transmitted the motor movements to the head's upper platform. However, since it was made of plastic, each piece bent slightly, and minor play resulted in the head being positioned lower than desired, even with motors correctly positioned, due to the head's front panel weight.



**(a)** **(b)**

**Figure 5.7.** Neck mechanism: (a) SPM neck mechanism testing setup, (b) 3D printed spherical gear neck mechanism.

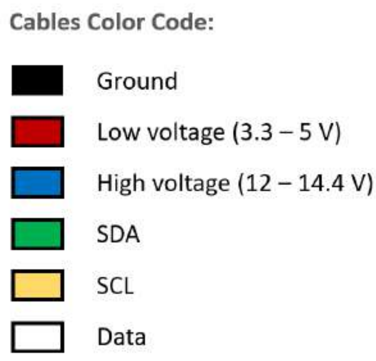
The issue prompted a **redesign**, leading to the development of the spherical gear mechanism presented in the previous chapter, which addressed these challenges and significantly improved the design. This mechanism was 3D printed in ABS and is shown in Figure 5.7b.

### 5.2.4. LEDs' Covers, Head Cables, Tactile Sensors and Modules

Next, the head front panel was assembled with the LCD display and the PVC sheet was cut and bent to adapt to the face shape, as it can be seen in Figure 5.8a. Between the LCD display frame and the PVC layer, a textile mesh layer was attached to make the color difference between the display background and the frame less noticeable.

Then it was decided to start making the connection cables for the head hardware components. In order to manufacture this home-made custom-length cables, a color code was established for easing cable identification once the whole robot is assembled. These color cables were cut with the needed length, crimped and then attached to DuPont-

**(a)**




**(b)**

**Figure 5.8.** Head wiring: (a) Head panels cable connections, (b) Cables color code.

type terminals. 3D-printed pieces were used to group several individual DuPonts in one single terminal. It was decided that to maintain the robot's modularity the head cables would only arrive to the neck height, and then extra cables would link these to the microcontroller. The cables were manufactured according to the connections diagram of Figure 4.31a and twisted to minimize electromagnetic interference. Figure 5.8b shows the used cable color code.

The polystyrene sheet was then cut with FabLab's laser cutting machine to obtain the LED rings' covers. These were attached to the head components using a silicon gun as shown in Figure 5.9. Also the forehead and ear tactile sensors were manufactured. In order to do this, two cables were connected to a copper sheet stuck to a silicon circular pad.

**Figure 5.9.** Head lateral panel assembly and connections.

The additional modules are designed to be connected through the male connectors embedded in the lateral panels. Each connector has 6 pins: power supply, ground, SCL and SDA for I2C communication and one analog and one digital GPIO ports. The cables for these modules can also be seen in Figure 5.9. The flashlight and gas detector modules were also 3D printed and assembled. Figure 5.10 shows the manufactured air quality and gas detector module.

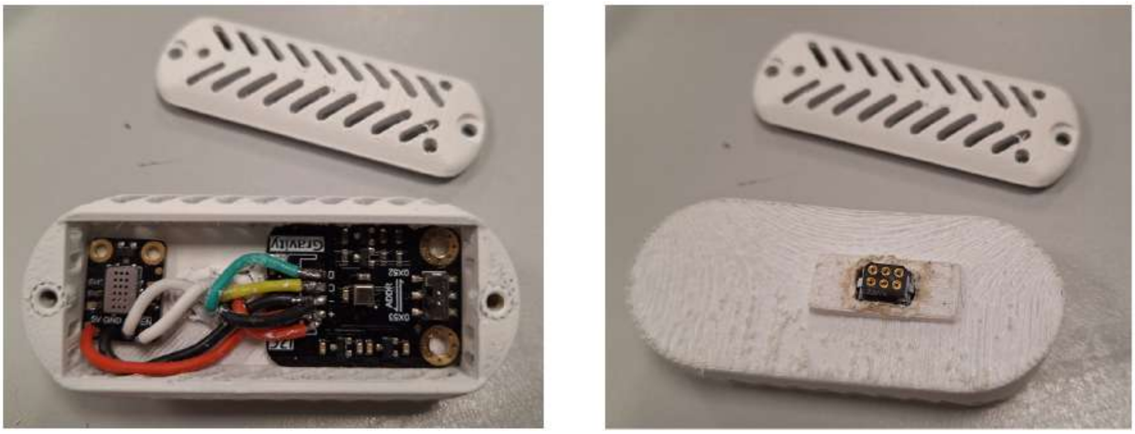


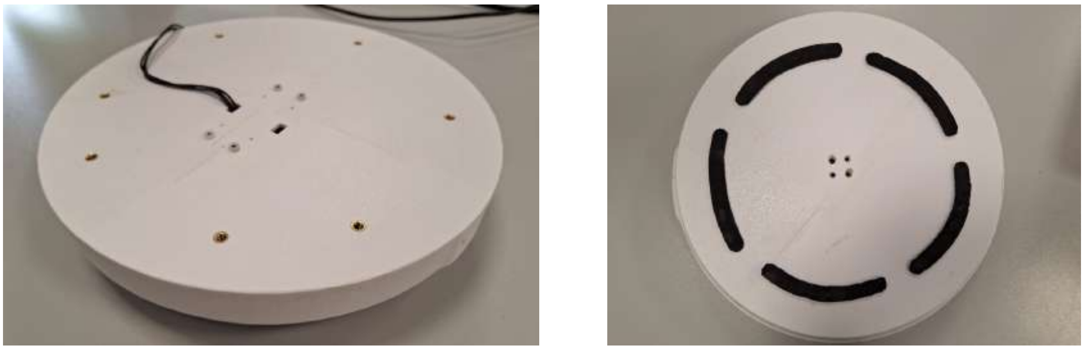
**Figure 5.10.** 3D printed air quality and gas detector module.

To finish with the head, the connectors were tagged in order to facilitate the connection between the body and head cables. Then, the whole head was assembled passing the cables through the holes designed for this purpose and grouped by mean of a textile tube as shown in Figure 5.11.

**Figure 5.11.** Cabled 3D printed head sub-assembly.

### 5.2.5. Base

Once the new PETG filament arrived, the base sub-assembly components were 3D printed. Once the printing process was completed, the base was assembled as shown in Figure 5.12a, introducing the brass threaded inserts and the corresponding bearings. Finally, the anti-slip foam adhesives were cut and stuck to the lower part of the robot' base as shown in Figure 5.12b.



(a) (b)

**Figure 5.12.** 3D printed base: (a) Top view, (b) Bottom view.

Then, the body support base was printed and threaded to the base, enabling the assembly of the complete robot internal structure. Once the Arduino protoshield connections were finished, the SSD together with the Jetson TX2i, Arduino block and USB hub were fixed to this base as it can be seen in Figure 5.13a.

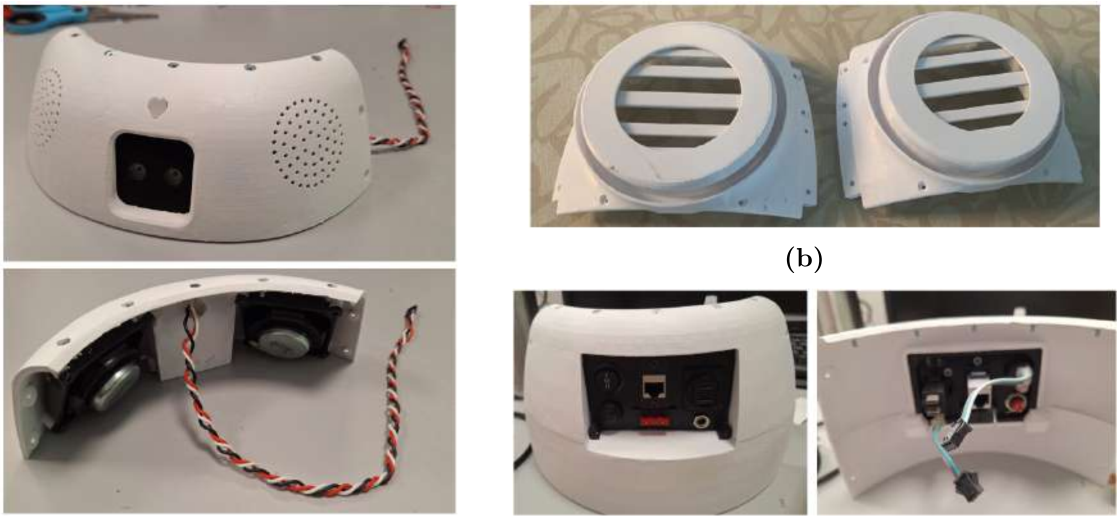
(a) (b)

**Figure 5.13.** Support and internal structure: (a) Body support base, (b) Front and back view.

### 5.2.6. Body

The final 3D prints included the front, back, and lateral casings of the robot's body. The lateral panels and covers are magnetically attached for easy access. To embed the magnets during printing, the printer was programmed to pause at the layer just before covering the holes designed to hold the magnets. This allowed the magnets to be inserted, after which the printing continued, securing and integrating them into the structure. The same process was followed for the head lateral panels and the back ports panel cover.

After the pieces were post-processed, the heartbeat LED polystyrene cover was glued to the front panel, as shown in Figure 5.14a. The speakers were also mounted onto the front panel, and the remaining body cables were fabricated and installed. Custom silicone touch pads were created and adhered to the lateral covers depicted in Figure 5.14b, in a similar way to the head ear covers. Lastly, the ports panel was affixed to the back body casing, as illustrated in Figure 5.14c.



(a) (b) (c)

**Figure 5.14.** 3D printed body panels: (a) Front body panel, (b) Lateral panels, (c) Back body panel.

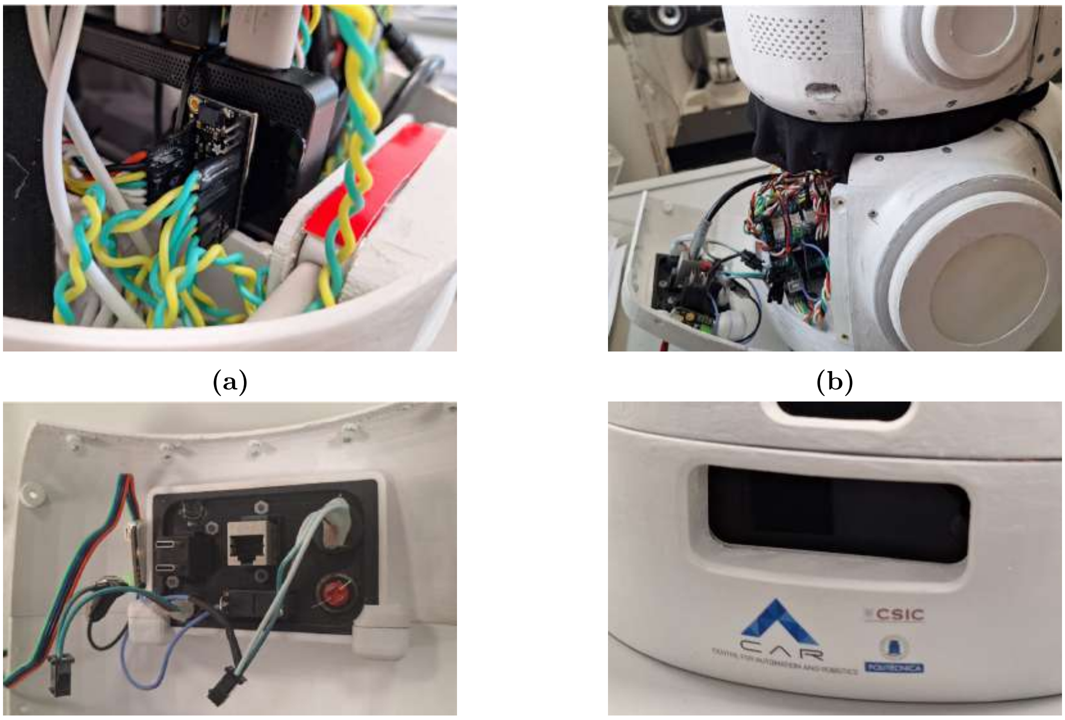
### 5.2.7. Final Details and Assembly

As the robot neared completion, several final details were carefully addressed to ensure both functionality and a polished appearance. The **installation** of the **missing sensors** and click modules was one of the last steps, with each component securely attached to the robot's body using double-sided tape, as shown in Figure 5.15a for the Adafruit MPR121. This method provided a reliable yet adjustable attachment.

The **elastic textile mesh** was then fixed to the head and body of the robot. It provided a clean and cohesive look by concealing internal components, while also enhancing safety by preventing fingers from accessing moving parts, as depicted in Figure 5.15b.

**Final wiring connections** were made, particularly in the **ports panel**, to ensure all electrical systems were fully operational. This included setting up mode switching between battery power and plugged-in operation, integrating fuse protection and wattmeter measurement, and securing all wires to prevent any loose connections, as illustrated in Figure 5.15c.

The last aesthetic touch was the application of a **waterslide decal** featuring the **CAR logo** on the front panel of the robot. After carefully positioning the decal, it was varnished to protect it from wear and enhance its durability, as shown in Figure 5.15d.




(a) (b) (c) (d)

**Figure 5.15.** Final manufacturing details: (a) Adafruit MPR121 installation, (b) Elastic textile mesh installation, (c) Ports panel wiring connections, (d) Logo decal.

With these final details completed, the robot's final assembly was conducted by threading the head sub-assembly to the spherical gear of the neck mechanism. The completed robot, with the head attached, is depicted in Figure 5.16b. This marked the culmination of the manufacturing phase, successfully integrating all design, fabrication, and assembly efforts into a cohesive and operational social robot.

(a) (b)

**Figure 5.16.** Final assembly steps: (a) Headless robot assembly, (b) Final robot assembly.

Chapter 6

# System Architecture and Firmware Development

This chapter provides an overview of the assistive robot's system architecture and firmware development. After outlining the key components of the system architecture, the chapter provides an overview of the firmware development process focusing on its architecture design, file structure, core functions, and the integration of third-party libraries and hardware components.

## 6.1. System Architecture Overview

The system architecture of the assistive robot is designed to enable complex emotional and empathetic interactions. This architecture is structured into **four layers** which can be seen in Figure 6.1, each serving a specific function while ensuring seamless integration between the robot's hardware, firmware, software, and input-output interfaces.

### 6.1.1. Software Layer

At the heart of this architecture lies the software layer, which orchestrates the robot's **high-level functionalities**. This layer is pivotal for managing the robot's interactions, ensuring that its responses are both emotionally aware and contextually relevant. This software layer was **inspired by the architecture used in Potato**.

In Potato, a socket communication system was employed to integrate its six modules, ensuring efficient coordination through a centralized state manager. Similarly, the soft-

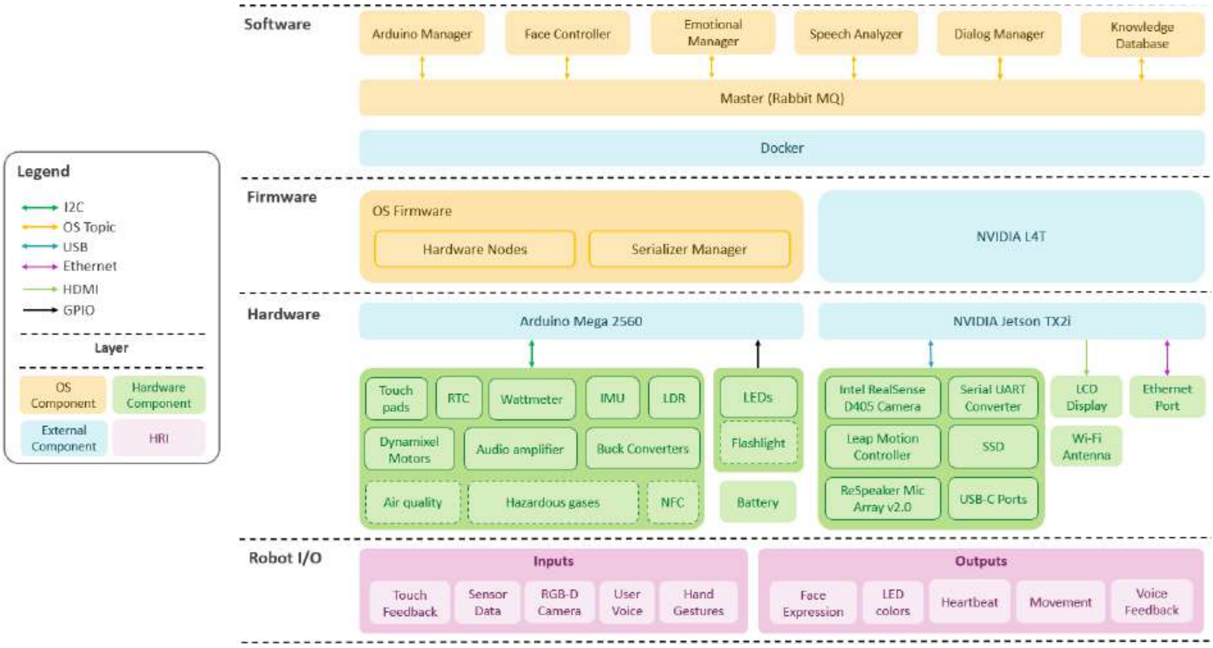



**Figure 6.1.** Robot general architecture.

ware layer of the robot built in this work adopts a **modular approach**, but with an enhancement in the form of **Docker-based containerization** developed in a different Master's Thesis. Each module, including the Arduino manager, face controller, emotional manager, speech analyzer, dialog manager, and knowledge database, operates within its own Docker container. These containers are orchestrated by a master module using Docker Compose, which coordinates the interactions and data flow between them. The modules are interconnected through the **AMQP protocol**, using RabbitMQ, enabling seamless communication and real-time processing. This setup is analogous to how ROS operates, where **each module functions as a node** that **publishes and subscribes to messages within topics**, ensuring efficient and organized data exchange.

This advanced setup, building on Potato's successful design, allows for more **scalable, flexible, and maintainable software** architecture. The use of Docker ensures isolation of modules, facilitating independent development, testing, and deployment, while Docker Compose streamlines the orchestration of the entire system. In the case of the **validation demonstration**, an application will be built in a **new container** that interconnects with the rest of modules.

### 6.1.2. Firmware Layer

Beneath the software lies the firmware layer, acting as the critical **bridge between software commands and hardware actions**. The Jetson TX2i leverages the external firmware provided by NVIDIA, known as NVIDIA L4T (Linux for Tegra). This firmware includes a Linux kernel, bootloader, and various drivers, facilitating the integration of high-level software with the underlying hardware. For the Arduino, a **custom firmware** was developed specifically for this robot. This firmware is structured around a **node-based architecture**, allowing for modular control of the different robot components.

To ensure effective communication between the Arduino Mega and the Jetson TX2i, a **serializer manager** was implemented within the custom firmware. This manager handles the serialization and deserialization of data, processing communications between the two systems. It ensures that commands from the Jetson TX2i are accurately executed by the Arduino Mega, and that the sensor data from the Arduino is correctly transmitted back for higher-level processing.

### 6.1.3. Hardware Layer

The hardware layer encompasses the **physical components** that enable the robot to interact with its environment. The **Arduino Mega** 2560 microcontroller manages **low-level operations**, interfacing directly with sensors and actuators, while the **NVIDIA Jetson TX2i** handles more **complex processing tasks** such as emotion detection and speech analysis. This hardware setup provides the necessary computational power and control to execute the robot's functions effectively.

### 6.1.4. Robot I/O Layer

Finally, the robot I/O layer integrates the input and output interfaces that **connect the robot to its external environment and users** according to the designed HRI. Input interfaces such as touch sensors, microphones, and cameras allow the robot to **gather data** about its surroundings and user input, facilitating real-time responsiveness. Output interfaces, including LED indicators, speakers, and the display screen, enable the robot to **express emotions and communicate effectively** with users. This layer ensures that the robot can perform **meaningful interactions**, translating the processed data from the higher layers into physical actions and sensory outputs that align with the robot's intended functions and user engagement tools.

## 6.2. Firmware Development

The custom robot C++ firmware aims to provide the necessary control mechanisms to allow the hardware to operate effectively under the software's guidance. Given the complexity of the robot's tasks, the firmware must be robust, flexible, and capable of real-time processing. This section delves into the proposed solution and specific functionalities to seamlessly integrate with both the hardware and software layers of the robot.

### 6.2.1. Firmware Architecture and File Structure

This section provides a detailed overview of the firmware's architecture and its file structure, offering insight into how the firmware components are integrated.

#### 6.2.1.1. Firmware Architecture

The firmware is structured to follow a **modular and node-based design**, where each node represents a distinct component or function within the robot, either sensors or actuators, as it can be seen in Figure 6.2. This architecture allows for the firmware to be highly flexible and scalable, enabling the addition of new modules or the modification of existing ones without affecting the overall system.

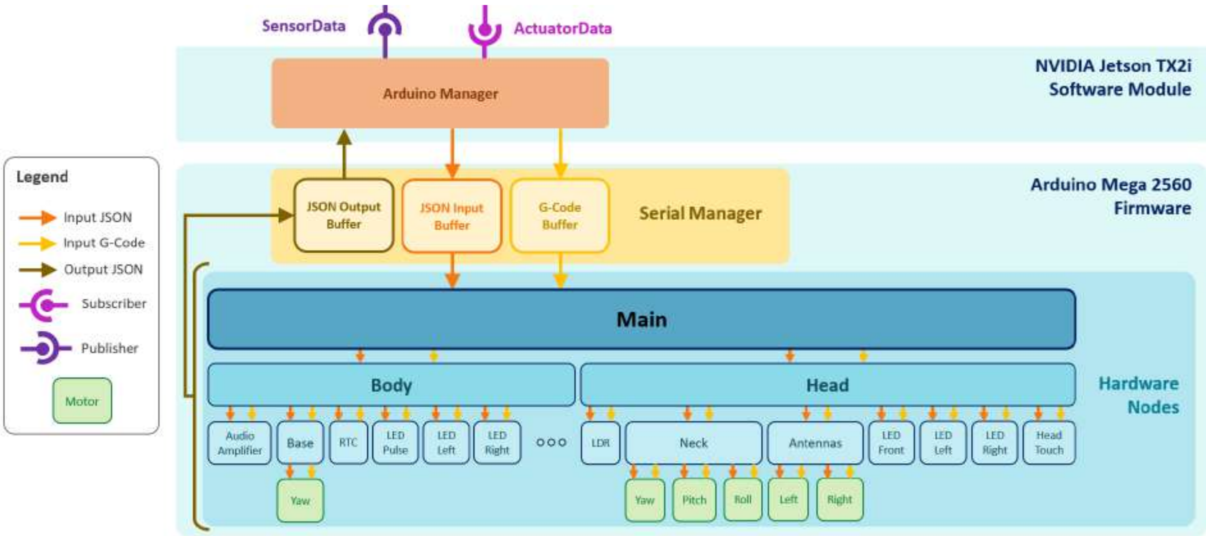



**Figure 6.2.** Firmware architecture.

As it can be seen in the figure, the firmware is composed of two main parts: the **hardware nodes** and the **serial manager**. The hardware nodes are hierarchic, being the main node composed of two sub-nodes: body and head. This way, each node can have as many sub-nodes as desired. The nodes are programmed by using a node abstract class, serving as base to create the rest of the nodes. Special types of nodes can be created to instantiate them as sub-nodes in an easier way. For example, this is the case of the motor node, instantiated as sub-node for the base, neck and antennas nodes.

With respect to the serial manager, it is responsible for handling all serial communication between the Arduino Mega and the NVIDIA Jetson TX2i. This class manages the transmission and reception of data, including **JSON** and **G-code** messages, through two input and one output buffers. An example of both types of message format can be seen in Figure 6.3a and 6.3b respectively. The JSON format is flexible but might be slow to parse, G-Code on the other hand is efficient and concise but less flexible.

```
//  JSON example:
//    <{"potato.head":{"led_front":{"on":1},
                       "led_left":{"on":1},
                       "led_right":{"on":1}},
        "potato.body":{"led_left":{"on":1},
                       "led_right":{"on":1}}}
```

(a)

```
//  G-Code example:
//    ~M01 0; // Turn all LEDs on
```

(b)

**Figure 6.3.** LEDs on message example: (a) JSON format, (b) G-code format.

#### 6.2.1.2. File Structure

The firmware's file structure is organized to support its modular architecture, with each module and its associated functionalities within specific files. This organization facilitates ease of development, debugging, and maintenance. Below is an overview of the key files and directories within the firmware:

- **`firmware.ino`:** It is the main entry point of the firmware, responsible for initializing the system, setting up nodes, and managing the main control loop. It orchestrates the overall operation of the robot as described in Algorithm 1. It is important to note that not all nodes are represented, as time constraints prevented the implementation of all the planned hardware devices.

**Algorithm 1** Firmware Initialization and Main Loop

```
Require: Firmware configuration, SerialManager, MainNode
Ensure: Initialization, input processing, and node control
Setup:
Initialize serialManager and mainNode
Start serial communication and motor system (if present)
Log firmware start and check all nodes are UNCONFIGURED
if nodes not UNCONFIGURED then
    Log error and exit
Configure and activate nodes
if any configuration or activation fails then
    Log error and exit
Log successful firmware start
Main Loop:
while loopCount is not zero do
    Process serial input
    if JSON or GCode received then
        Handle input and clear received flag
    Send JSON response, loop all nodes
    Track loop time and handle any overrun
    Decrement loopCount (if debugging)
Shutdown:
Deactivate, cleanup, and shutdown nodes
if nodes not in final state then
    Log error and exit
Log firmware exit and terminate
```

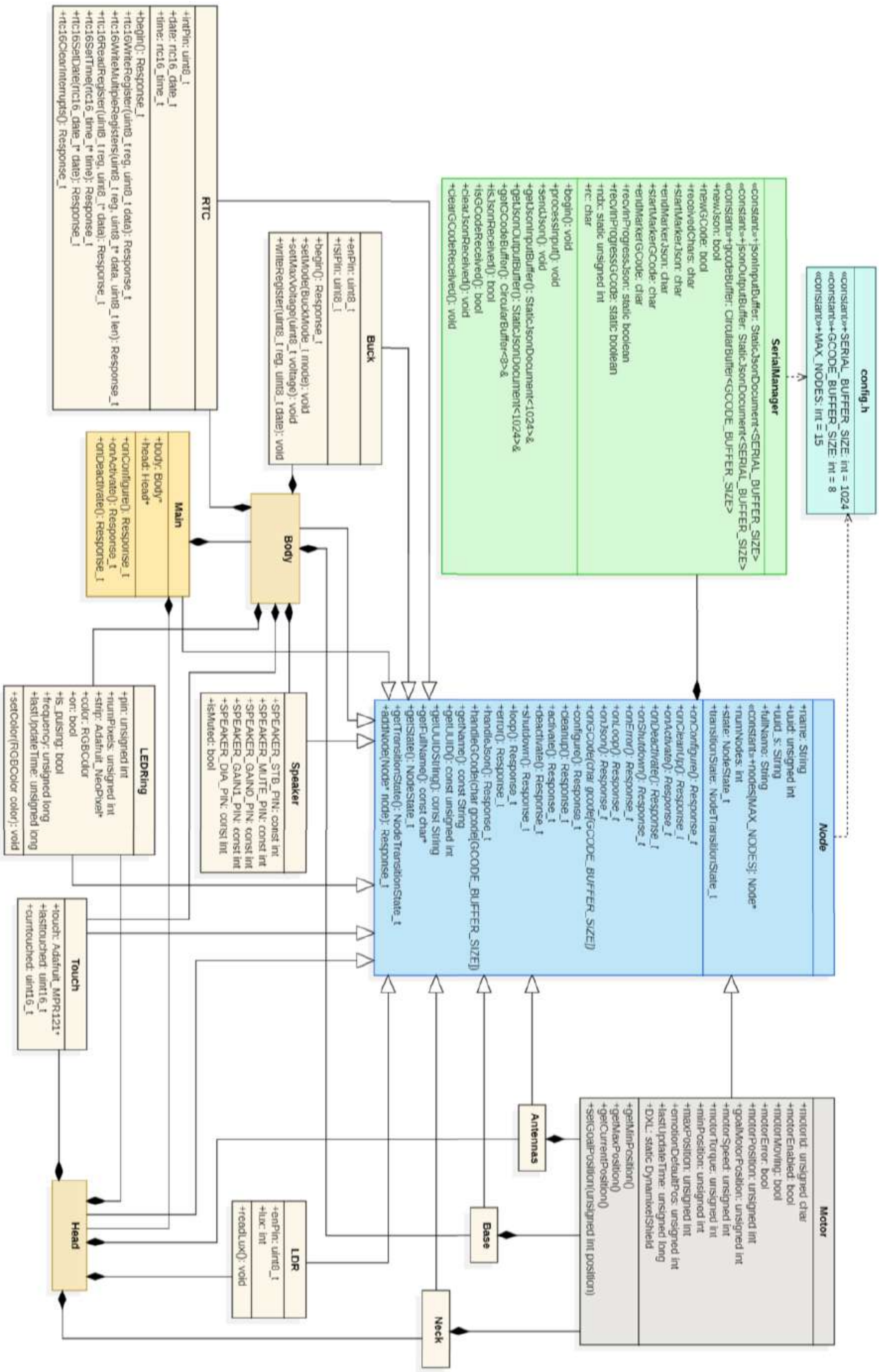



**Figure 6.4.** Firmware UML diagram.

- **`config.h`:** A configuration header file that defines global constants, such as pin assignments, serial communication settings, and node configurations. This file centralizes all configurable parameters, making it easy to adjust settings without modifying the core codebase.

- **`src/`:** This directory contains the core source files that implement the firmware's functionality.

  - **`node.hpp` and `node.cpp`:** Define the abstract `Node` class, which is the base class for all nodes in the firmware. This class manages state transitions and provides a framework for creating new nodes.
  - **`serial.hpp` and `serial.cpp`:** Implements the `SerialManager` class, handling all serial communication tasks, including parsing incoming messages and formatting outgoing data.
  - **`main.hpp` and `main.cpp`:** Define the `Main` class, which serves as the root node for the firmware. It aggregates all other nodes (e.g., body, head) and manages their interactions.
  - **`nodes/`:** This directory contains header and source files for specific nodes, each corresponding to a particular component of the robot (e.g., `body.hpp`, `body.cpp`, `led.hpp`, `neck.hpp`,...). Note that since this was an initial prototype version, due to time constraints it was not possible to define the full functionality of all the nodes, such as the one for controlling the neck motors.
  - **`3rdparty/`:** A directory for third-party libraries that are integrated into the firmware. These libraries provide additional functionality, such as JSON parsing, circular buffers, and logging.

### 6.2.2. Firmware Core Functions

The firmware for the robot is designed with key principles that ensure its robustness, modularity, and efficiency, directly translating into its core functionalities. This integrated approach ensures that the robot can perform complex tasks reliably and adapt to future enhancements. The following key aspects illustrate how these principles are implemented in the firmware:

1. **Modularity and node-based architecture:** The firmware is built on a node-based architecture where each node represents a specific hardware component or subsystem, such as sensors or actuators. This modular design enables independent development, testing, and integration of various components. Nodes can be individually configured, activated, deactivated, and cleaned up, which enhances the

system's maintainability and allows for scalability as new features or hardware are added. Furthermore, the hierarchical node structure ensures that each node is responsible for initializing and managing its sub-nodes.

2. **State management and separation of concerns:** Each node operates within a structured framework that includes distinct states: unconfigured, inactive, active, and finalized. This separation of states ensures that each component of the robot performs predictably and can be easily debugged and maintained. The firmware includes routines for state transitions, configuration, activation, error handling, and shutdown, ensuring that the system remains reliable under various conditions.

3. **Efficient communication and data handling:** Communication between the NVIDIA Jetson TX2i and the Arduino Mega microcontroller is managed by a custom serial manager. This module processes and serializes data exchanged between the two systems, ensuring low latency and optimizing real-time performance. The use of JSON for structured data and G-Code for command instructions allows the firmware to handle complex communication efficiently. Additionally, the serial manager includes a recursive mechanism that checks for incoming messages across all nodes, ensuring that each node processes relevant JSON and G-Code messages.

4. **Scalability and flexibility:** The firmware is designed to be scalable and flexible, accommodating the addition of new nodes or functionalities with minimal modifications. The modular architecture and use of configuration files make it easy to expand the system's capabilities, which is crucial as the robot evolves to meet new requirements or integrate additional hardware.

5. **Robust error handling:** Each node incorporates error handling routines to manage unexpected conditions. Whether dealing with configuration errors, communication failures, or runtime issues, the firmware is equipped to detect and respond appropriately. This typically involves transitioning the affected node to a safe state and logging the error for further analysis, ensuring the overall system's robustness.

6. **Real-time processing and loop efficiency:** The firmware's main loop is designed to execute all necessary operations, such as processing inputs, managing communications, and executing node-specific tasks, within as fixed time frame. This real-time processing is critical for the robot's responsiveness. The loop is monitored for any delays, and if it exceeds the expected duration, the firmware logs an error to help identify and address performance issues promptly.

By adhering to this principles, the firmware ensures that the robot operates reliably and efficiently, with a structure that supports complex, real-time interactions with its environment. This robust design framework underpins the robot's ability to perform its tasks effectively, offering a foundation that can adapt to future enhancements or modifications.

### 6.2.3. Third-Party Libraries and Hardware Integration

The firmware for the robot leverages several third-party libraries to ensure reliable communication, efficient data handling and processing, and monitoring and debugging capabilities.

Three external libraries were used for developing the firmware architecture: ArduinoJson [119], CircularBuffer [120] and EasyLogger [121]. **ArduinoJson** was employed for efficiently serializing and deserializing JSON data, crucial for structured communication between the robot's microcontroller and other components. **CircularBuffer** managed the real-time storage and retrieval of incoming G-Code commands, ensuring smooth, sequential processing without data loss. Finally, **EasyLogger** provided a flexible logging mechanism, enabling detailed tracking and debugging of system events. This enables to work with two firmware versions: release and debug, depending on the desired amount of logging.

In addition, proprietary libraries from manufacturers were utilized to configure hardware components like the Adafruit MPR121, LED rings, LDR sensor, and Dynamixel motor firmware nodes. For other sensors and actuators, such as the buck converter, audio amplifier, and RTC, which lacked dedicated libraries, macros were defined to represent register addresses, enabling direct interaction with the hardware through register read and write operations.

## 6.3. Software Integration

The integration of the firmware with the software architecture is a critical aspect of the robot's functionality, ensuring that the hardware components are seamlessly controlled and coordinated by the high-level software modules. This integration is achieved through a well-defined architecture that allows for efficient communication, real-time processing, and modular development.

### 6.3.1. Software Architecture Overview

Figure 6.5 illustrates the interaction between the various modules of the robot's software architecture through publication and subscription to topics using RabbitMQ.

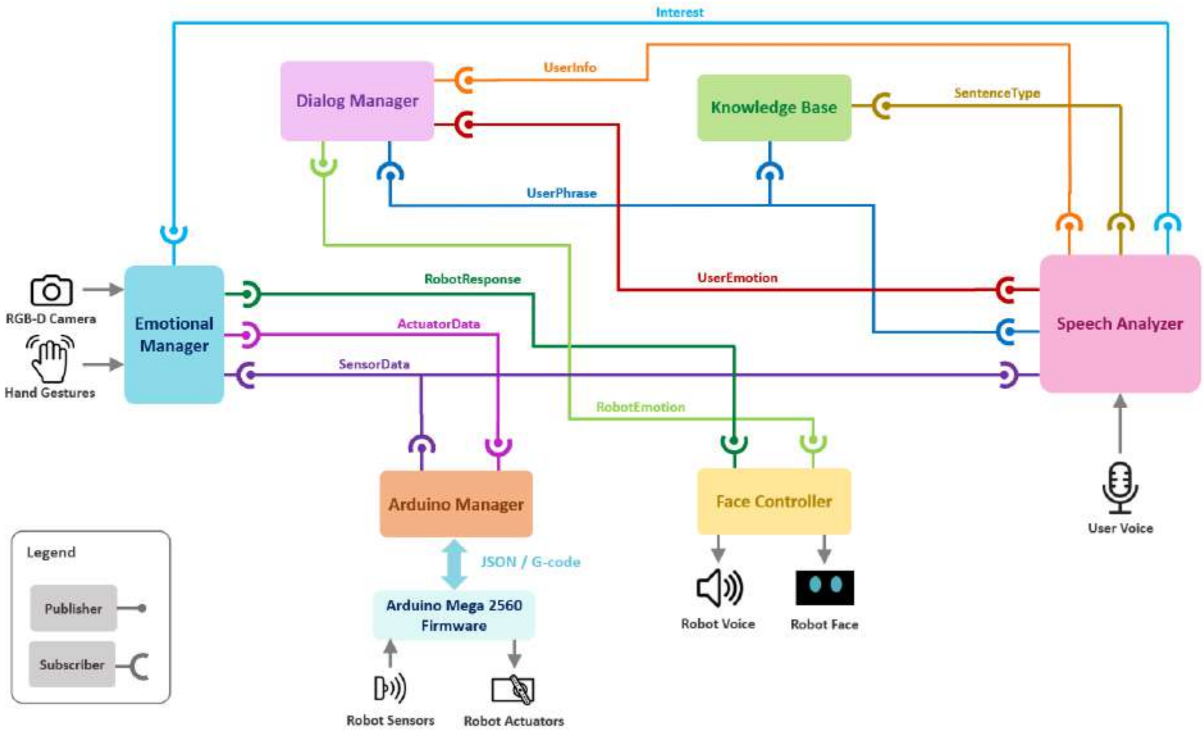



**Figure 6.5.** Complete software architecture.

The software architecture based on the one of Potato is designed to manage complex interactions and ensure the robot responds appropriately to user input and environmental changes. This architecture is modular, with each component responsible for a specific aspect of the robot's behavior. The key modules are:

1. **Emotional manager:** This module processes inputs from various sensors and interprets the user's emotional state, generating an appropriate emotional response that is sent to other modules for further action.

2. **Dialog manager:** Handles the flow of conversation with the user. It ensures that the robot's verbal responses are coherent, contextually appropriate, and aligned with the detected emotional state.

3. **Arduino manager:** Acts as the bridge between the high-level software modules and the physical components managed by the Arduino microcontroller. It processes sensor data and sends commands to actuators.

4. **Face controller:** Manages the robot's facial expressions, translating emotional data into visual outputs that reflect the robot's current state or response.

5. **Speech analyzer:** Analyzes the user's vocal input to detect emotional cues, speech patterns, and other relevant data, which is then fed back into the system for processing by other modules.

6. **Knowledge base:** Stores user-specific information, historical interactions, and contextual data, enabling the robot to make informed and personalized responses.

The detailed internal functioning description of some of these modules is out of the scope of this work since they were developed for Potato and they have not been implemented yet in the new robotic platform designed in this project.

### 6.3.2. Simplified Version Implementation

While the complete software architecture comprises six modules, a simplified version, shown in Figure 6.6, has been implemented for the current stage of development. This version includes **three core modules**:

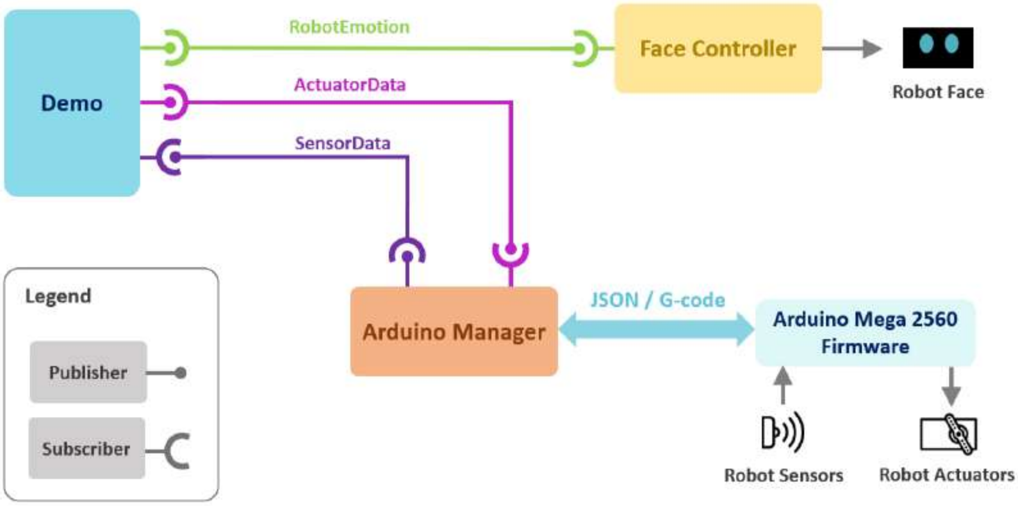



**Figure 6.6.** Simplified software architecture.

- **Demo module:** This module subscribes to sensor data and publishes emotion data and actuator commands. It is the main application and serves as a demonstration of the robot's capabilities, showing how sensor inputs can influence the robot's emotional state and actions.

- **Face controller module:** This module subscribes to the emotion data published by the Demo Module. It controls the robot's facial expressions, ensuring that they align with the detected emotional state.

- **Arduino manager module:** This module is responsible for interfacing with the Arduino Mega microcontroller. It publishes sensor data and subscribes to actuator commands, acting as a bridge between the robot's hardware and the rest of the software system.

For each topic, specific message types are defined similarly to how it is done in ROS. Sensor data is transmitted using a JSON-structured message, whereas actuator data is sent as G-code string messages. Additionally, JSON can also be used for actuation-related communications. This simplified architecture provides a functional prototype, enabling initial testing and validation of the robot's core capabilities. As development progresses, the additional modules will be integrated, bringing the system closer to its full potential.

Chapter 7

# Results and Discussion

This chapter presents a detailed analysis of the outcomes derived from the testing and validation phases of the robot's development. It explores the extent to which the design requirements where met, evaluates the performance of the mechanical and electronic systems, and discusses the results of various tests conducted on sensors, actuators, and firmware. Additionally, the chapter provides an in-depth overview of the demonstration process, detailing its objectives, development, and integration. The insights gained during these stages are discussed, highlighting key findings, challenges encountered, and potential areas for future improvement.

## 7.1. Assessment of Design Objectives

This section assesses the robot's design against the initial functional and performance requirements, evaluating how well the implemented design meets these goals. Each requirement is reviewed in terms of its fulfillment, limitations encountered, and potential areas of improvement.

- **Compactness and stability:** The robot's design successfully achieved a compact and relatively lightweight structure. The robot is around 40 cm tall when the antennas are disassembled, has a diameter of around 27 cm and weights a bit more than 8 kg, with optimized space for all its hardware components and wiring. Stability proved to be very good thanks to the anti-slip foam pads. Even when the base rotates at high speed the inertia of the robot is not able to unbalance it.
- **Maintenance:** The design allows for easy access to internal components, simplifying maintenance and repairs, particularly for the battery, as it can be seen in Figure

7.1. The modularity of the design ensures that components can be accessed and replaced efficiently, fully meeting this requirement.

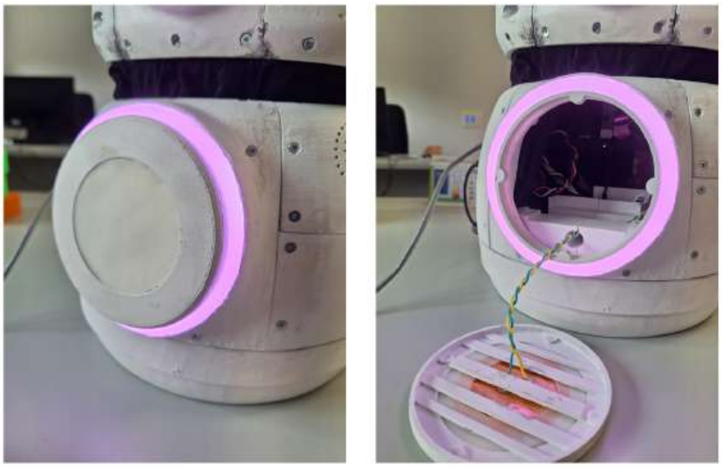


**Figure 7.1.** Robot's right lateral panel for battery placement.

- **Power management:** The robot can operate effectively both on battery power and when plugged in. However, the battery did not arrive on time for its implementation in the robot so its battery life could not be tested. Rough estimations considering the maximum current measured on the motors and the consumption of the LEDs indicate that it might be able to last 3 hours under normal usage.

- **Air refrigeration:** This requirement could not be tested since the Jetson TX2i was not submitted to heavy computation tasks and several hardware elements were not implemented due to time constraints. It was qualitatively seen that the areas were the LED rings were warmed up but the PETG should be able to resist these temperatures well enough.

- **User-friendly and ergonomic design:** The robot's design was well-received by lab members specialized in social robotics, who provided positive feedback on its approachable appearance, validating the design's effectiveness in a controlled setting. However, further testing is required to evaluate its reception by the target users, particularly in real-world scenarios involving children and elderly individuals, to ensure that the design meets the intended user experience and comfort standards.

- **Cost optimization:** The total material cost for the robot project was approximately 3.500 € as it can be seen at Table C.1 in Appendix C. While efforts were made to optimize costs, the necessity to purchase from specific providers to streamline bureaucracy with the university led to higher expenses for some components. It was observed that significant discounts could have been achieved with alternative suppliers. Moreover, the iterative nature of the design and manufacturing process resulted in a small number of components being discarded. Despite these challenges, the project remained within its budget, though there is potential for further cost reductions in future iterations by exploring more flexible procurement strategies and avoiding unnecessary purchases.

- **Flexibility and customization:** The design supports future upgrades and customization with the possibility to create and connect additional modules in the head laterals. Since the robot's head is similar in size to a human's, it can also incorporate human accessories such as a cap or hat, further enhancing its customization potential. This flexibility allows the robot to adapt to different environments and user preferences, making it more versatile and relatable in various social robotics applications.

- **Emotion display and interaction:** A key objective was for the robot to display basic emotions effectively. This was accomplished through facial expressions, body movements, and LED indicators. The integration of these features allowed the robot to engage users emotionally, enhancing the overall interaction experience. However, the emotional display system could be expanded in future versions to include a broader range of emotions and more nuanced expressions.

- **Ease of assembly and component integration:** The robot was designed for easy assembly and disassembly, which was crucial for maintenance and potential upgrades. The component integration was carefully planned to ensure that all compulsory and optional components were seamlessly incorporated into the design . This requirement was fully met, with the assembly process being straightforward and well-documented. However, some pieces could have benefited from a more optimized design, as certain steps in the assembly process could have been more comfortable.

- **Minimum functionalities:** All required functionalities, such as tactile interaction and audio communication, were successfully implemented and tested, confirming that the robot meets the essential functional criteria.

Overall, the design requirements were largely met, with only a few areas identified for potential improvement. These findings will inform future development efforts, ensuring that the robot continues to evolve to meet user needs and technical challenges.

## 7.2. System Testing and Validation

This section presents the testing and validation process for the robot, focusing on mechanical performance, sensor and actuator functionality, and firmware efficiency. Given that the robot is in the very early stages of development, these tests are primarily **qualitative** in nature. The challenge in finding quantitative metrics for some aspects of the robot's performance also contributed to this qualitative focus. Nonetheless, the tests conducted provide valuable insights into the robot's current capabilities and areas for improvement.

### 7.2.1. Mechanical Testing

During the mechanical testing phase, the first prototype of the neck mechanism was found to be inadequate, as it lacked the necessary strength to lift the robot's head. This initial failure highlighted the need for a redesign. The new mechanism, which incorporated a more robust structure and improved gearing, was subsequently tested and demonstrated the ability to perform full-range movements without difficulty. However, it was noted that the redesigned mechanism exhibited a slight amount of backlash. This could be attributed to minor play within the spherical gear mechanism. For future iterations, this issue could be mitigated by increasing the top cover of the spherical gear, shown in Figure 7.2, which would help to reduce the backlash and enhance the overall precision of the movements. Note that the top cover had this partially-covering design for enabling easy assembly. In case this modification is done, it would be required to divide the top cover into two parts.

**Figure 7.2.** Detail of the top cover of the spherical gear mechanism.

Additionally, during these tests, an ammeter was connected to measure the current consumed by the motors while lifting the head and performing full-range movements. The results showed that the current peaks **did not exceed 0.6 A** for two motors operating simultaneously. Given that the robot has a total of six motors—four larger ones and two smaller ones—the maximum estimated current demand would be less than 5 A at peak, which aligns well with the battery's maximum current supply capability. This results seemed to indicate that there is enough margin for the power consumption of the NVIDIA Jetson TX2i, known to have significant current demands, especially under high computational loads. The current drawn by other components such as sensors and actuators, is relatively negligible compared to the motors and the Jetson TX2i.

### 7.2.2. Sensor and Actuator Testing

The testing of the robot's sensors and actuators was conducted in a structured manner, beginning with unitary tests of individual components and progressively integrating additional hardware into the firmware. This approach allowed for the isolation and identification of potential issues, ensuring that each element functioned correctly before advancing to more complex integrations. Due to the **limited timeframe, exhaustive testing**, validation, and full integration of all hardware components **were not possible**, but the primary components were evaluated as follows.

#### 7.2.2.1. LDR

The LDR was tested to assess its ability to detect changes in ambient light level. The LDR was integrated in the firmware using the third-party library provided by the manufacturer, and its responsiveness was evaluated by exposing it to varying light conditions. The tests demonstrated that the LDR could reliably detect changes in light intensity, providing accurate data for potential use in environmental awareness features.

However, it was observed that the LDR took approximately **4 seconds to update** light intensity values, even with the shortest firmware loop rate possible of around 200 ms. This delay suggests that the issue likely stems from the LDR hardware or its associated library, rather than the firmware. Future research could explore the possibilities offered by the current library to determine if improvements in responsiveness can be achieved or if the hardware inherently requires such a long acquisition time.

#### 7.2.2.2. Touch Pads

The touch pads were tested to ensure they could detect user interactions with the robot. Each pad was connected individually to the Adafruit MPR121, which was connected to the Arduino Mega through I2C, and a series of touch gestures were performed to evaluate sensitivity and accuracy. The touch pads showed consistent performance, successfully detecting light touches and more deliberate presses. However, it was noted that very light caresses were not consistently detected, indicating that the sensitivity might not be fully optimized. This suggests that further calibration of the Adafruit MPR121 might be necessary to improve the responsiveness of the touch pads to lighter touches.

#### 7.2.2.3. LEDs

The LEDs were tested to validate their ability to display a range of colors and intensities, which are used for emotional expressions and signaling. Each LED module was activated via the firmware, and a sequence of color changes was commanded. The LEDs performed as expected, producing bright and distinct colors, as it can be seen in Figure 7.3. In addition to this, custom G-codes were programmed in the firmware to ease the most common operations with the LEDs, turn them all on, all off, and set them to the color associated to a certain emotion. The heartbeat LED was configured to run individually in a pulsing mode with a frequency determined by its emotional state. The tests confirmed that the LED system is capable of conveying emotional states effectively.

**Figure 7.3.** LED rings testing.

#### 7.2.2.4. LCD Display

The LCD display was tested to ensure it could accurately present the visual information, including facial expressions and user interface elements. It was also checked the elastic mesh added for aesthetic purposes did not impede proper visualization, as it can be seen in Figure 7.4. The display was connected through HDMI to the Jetson TX2i and functioned correctly, with sharp image quality and responsive display changes. Additionally, the Jetson was configured to not display the cursor and the window top bar from the Python script-generated images, ensuring that only the face itself was shown on the screen, providing a cleaner and more immersive visual experience.

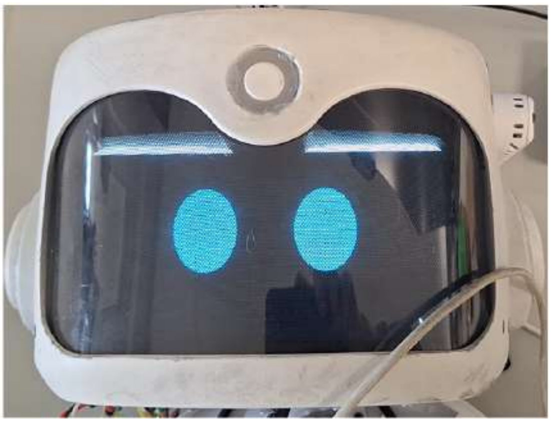


**Figure 7.4.** LCD display testing.

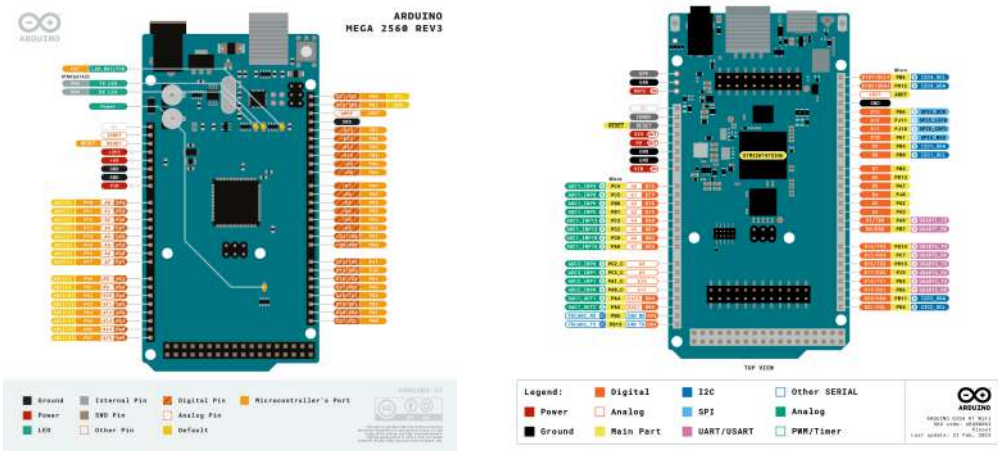
### 7.2.3. Firmware Performance Testing

The firmware performance testing revealed a significant limitation with the Arduino Mega 2560 microcontroller due to its constrained **dynamic memory** capacity of just **8 kB**. This limited memory means that the Arduino Mega can only run a few nodes simultaneously. Specifically, it was tested to be able to run properly 13 nodes corresponding to the base motor, heartbeat LED, body and head LED rings, LDR sensor and front head tactile pad with their respective parent nodes. This restriction significantly impacts the robot's ability to perform complex operations with all its hardware components engaged simultaneously, leading to a need for careful management of the active nodes to avid exceeding the memory capacity.

To mitigate this issue, the firmware was tested by selectively deactivating certain nodes, allowing to test some nodes in isolation. This testing approach provided useful insights into the performance of the firmware under various configurations, confirming that while the Arduino Mega can handle basic operations, it struggles to manage the full array of nodes without encountering memory-related performance issues.

Despite these limitations, the firmware's communication using JSON and G-code messages wasa tested and shown to work correctly. This successful communication is crucial as it underpins the interaction between the robot's subsystems, ensuring that the commands and data are accurately transmitted and executed.

Looking ahead, the **Arduino Giga R1 WiFi** [122] presents a promising upgrade path. With a substantially larger dynamic memory capacity of 1 MB, **125 times more** than the Arduino Mega, this microcontroller can support a far greater number of simultaneously active nodes. This enhancement would enable the robot to fully utilize all its hardware components without the need for deactivating certain nodes to manage memory limitations. The Arduino Giga R1 WiFi also shares the same form factor as the Arduino




(a) (b)

**Figure 7.5.** Arduino layout comparison: (a) Arduino Mega 2560 [110], (b) Arduino Giga R1 WiFi [122].

Mega, and has very similar connection ports, as shown in Figures 7.5a and 7.5b, meaning that only minimal modifications would be required to the existing protoshield connections to accommodate this upgrade.

Incorporating the Arduino Giga would not only resolve the current memory limitations but also significantly enhance the robot's overall performance, responsiveness, and ability to execute more complex tasks simultaneously. This upgrade would be a key step forward in realizing the full potential of the robot design and capabilities.

## 7.3. Demo Description and Integration

Given the memory limitations of the Arduino Mega, the demo development had to be meticulously planned to optimize the use of available resources. The initial comprehensive plan was revised to focus on critical components, including the base motor for primary movement, the LCD display for facial expressions, the LED rings for emotional cues, the heartbeat LED, the front head touch pad for user interaction, and the LDR for ambient light detection. Figure 7.6 shows the interactive flow of the proposed demo.

The demo was conceptualized as a state machine due to the absence of higher-level modules such as the emotional manager, dialog manager, knowledge base, and speech analyzer. This approach allowed for deterministic behavior based on specific inputs, ensuring predictable and manageable interactions within the constrained environment. The interaction flow is structured as follows:

1. **Initial state (normal):** The robot starts in a neutral emotional state. The LCD display shows a neutral face, and the LED rings are set to a calm blue color.

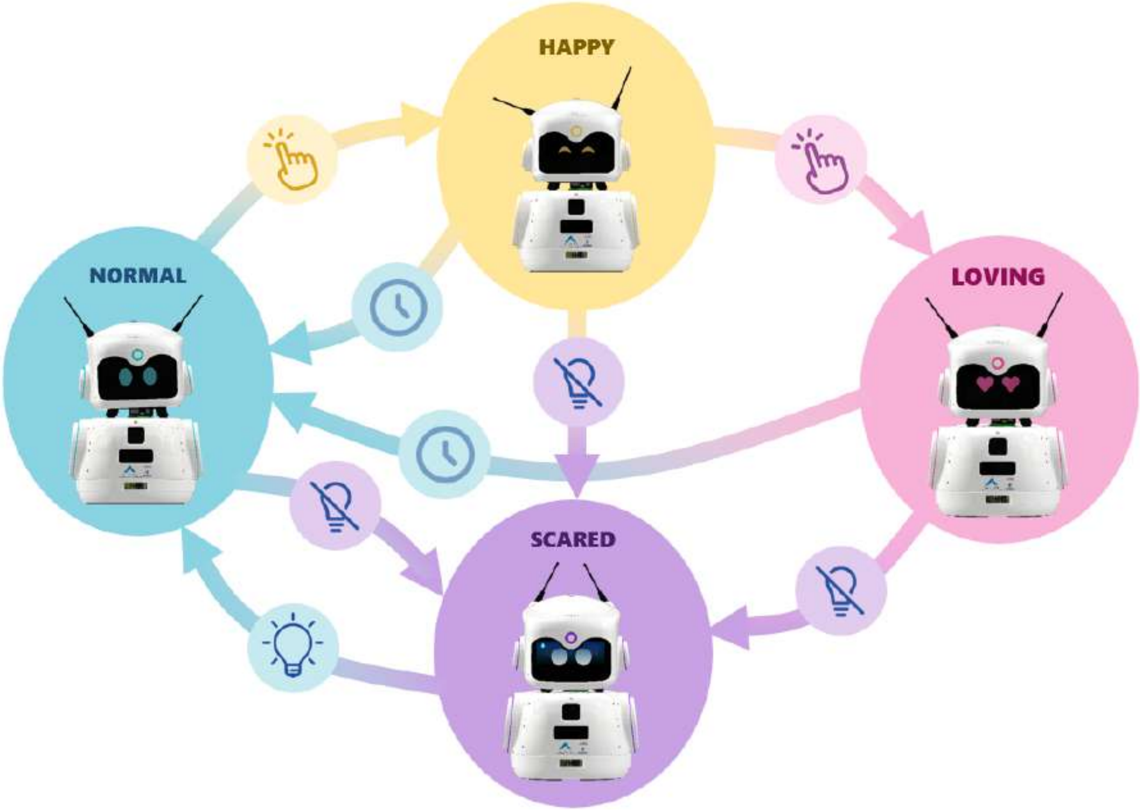



**Figure 7.6.** Demo state machine diagram.

2. **Touch detected:** When the touch pad is activated, the robot transitions to the happy state. The LCD displays a happy face, the LED rings turn yellow, and the heartbeat LED pulses more rapidly. This happy state will remain during a certain time and then go back to normal again. If the robot is touched again when it is happy, then it will turn into loving state, with pink color LED rings. In the loving state, the base motor is activated to demonstrate a simple movement, symbolizing the robot's excitement or eagerness.

3. **Light level change:** The LDR continuously monitors ambient light levels. If a significant drop in light level is detected, the robot transitions to the scared state. The LCD displays a scared face and the LED rings turn purple, with the heartbeat LED pulsing rapidly. After the light level returns to its initial value, the robot will return to its normal state.

This simplified demo highlights the core interactions possible within the current hardware limitations, effectively showcasing the robot's ability to change states based on touch and light inputs. Additionally, the firmware's communication through JSON and G-code messages was confirmed to be working properly during the demo. Figure 7.7 shows the robot in various states, displaying different emotions as part of the demo, illustrating its ability to express emotions through visual outputs.

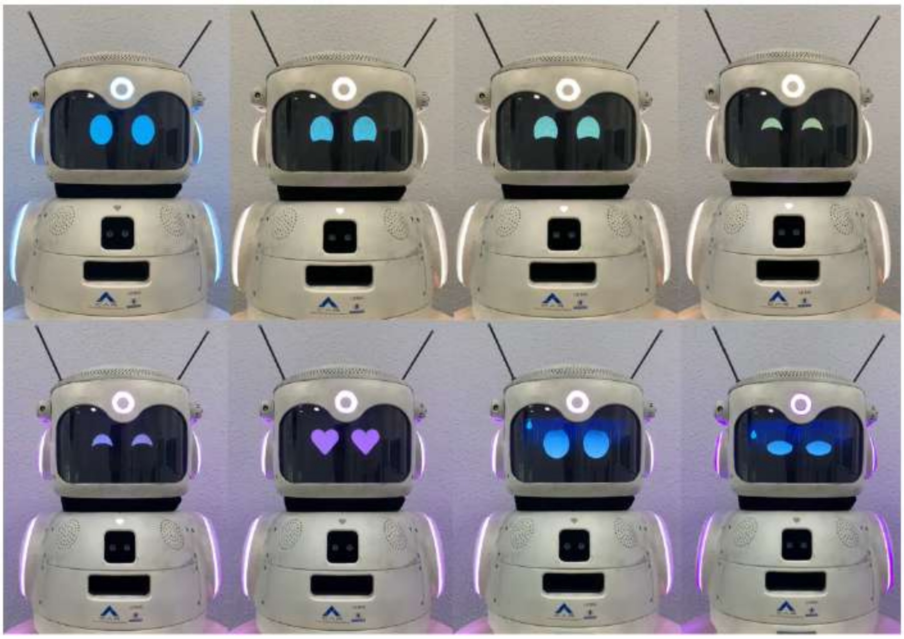


**Figure 7.7.** Robot's demo animated states.

While the demo was more limited than initially planned, it successfully demonstrated the integration of various sensors and actuators, providing a solid foundation for future enhancements as more powerful hardware components, such as the Arduino Giga, are incorporated.

## 7.4. Summary of Key Findings

The results from the testing and validation phases revealed several critical insights into the robot's design, performance, and functionality. Key findings from this chapter include:

- **Design requirements fulfillment:** The robot's design largely met the initial requirements, achieving a compact and stable structure, ease of maintenance, and effective power management. However, certain areas, such as air refrigeration and user reception, require further testing and validation.
- **Mechanical and structural performance:** The mechanical testing identified initial weaknesses in the neck mechanism, which were successfully addressed in the redesign. The improved mechanism demonstrated reliable performance with minimal backlash. The current measurements confirmed that the robot's power system is adequately designed to meet the demands of the motors and the Jetson TX2i.
- **Sensor and actuator functionality:** The sensors and actuators performed as expected during unitary and progressive tests, with the LED rings, LCD display,

LDR, and touch pads all functioning effectively. However, some limitations were noted, such as the LDR's slow responsiveness and the need for further calibration of the touch pads to detect light caresses.

- **Firmware performance:** The Arduino Mega's limited dynamic memory was identified as a significant constraint, allowing only a subset of nodes to run simultaneously. Despite this limitation, the firmware successfully managed communication through JSON and G-code messages. The potential upgrade to the Arduino Giga R1 WiFi was highlighted as a solution to overcome these limitations.

- **Demo development:** The demo was adapted to showcase the robot's core functionalities within the constraints of the available hardware and firmware. By focusing on key interactions, such as touch detection, light sensitivity, and emotional display; the demo effectively demonstrated the integrated performance of the robot's primary components.

These findings provide a clear direction for future development, emphasizing the need for hardware upgrades, further testing, and expanded functionality to realize the full potential of the robot's design.

Chapter 8

# Conclusions and Future Work

This final chapter summarizes the key findings and accomplishments of the project. It reflects on the project's outcomes and the overall success in meeting the initial objectives. Furthermore, this chapter outlines potential future work and areas for further research and development, aimed at enhancing the robot's capabilities, improving its design, and expanding its application scope.

## 8.1. Main Conclusions

The development of the social robot presented in this work has been a significant achievement, providing a solid foundation for future research and development in personal assistance robotics. The project **successfully met its primary objectives** by delivering a sophisticated hardware platform that integrates mechanical design, electronic components, and firmware development, all geared towards enhancing human-robot interaction.

A key goal was to create a robot with a modular and robust design capable of **advanced interaction capabilities**. This was achieved through a well-thought-out mechanical design, resulting in a compact, stable structure that not only facilitates easy access to internal components but also ensures the robot is **user-friendly and maintainable**. The integration of essential hardware components equipped the robot with the tools necessary to effectively interact with its environment. The design also prioritized emotional engagement, with the successful development and integration of animated **emotional expressions** into the robot's interaction system, demonstrating its potential to connect with users on a deeper level.

The firmware, although constrained by the **limitation of the current microcontroller**, laid a solid foundation for controlling the robot's basic functions. The hierarchical node firmware architecture introduced in this project is a promising start that, with more powerful hardware, can fully exploit the robot's capabilities. The **modular approach** in both hardware and software ensures that the robot can be continually enhanced, allowing for future upgrades and the addition of new functionalities.

The integration and testing phase proved that the robot could function as a cohesive system, validating the design and implementation decisions made throughout the project. Despite some challenges, particularly in fully deploying the firmware and integrating all planned components, the project has met its key objectives. The robot's design is both **functional and aesthetically appealing**, setting the stage for future developments.

In conclusion, this project has successfully created a **sophisticated hardware platform for a social robot**, laying the groundwork for future advancements in personal assistance robotics. While there are areas for improvement, the results achieved represent a significant contribution, offering numerous opportunities to continued research and development. The project's success in meeting its objectives underscores its potential to advance the capabilities of social robots in **real-world applications**.

## 8.2. Future Work Lines

The project opens several avenues for future research and development. These include enhancing the robot's interaction capabilities, improving its mechanical design, and expanding its application areas. Future work can be grouped into several key categories: design and hardware enhancements, firmware and software improvements, and simulation. Each area offers potential for significant advancements that can enhance the robot's capabilities, usability, and performance.

### 8.2.1. Design and Hardware Enhancements

- **Neck Mechanism Improvement:** While the developed spherical gear neck mechanism meets the required torque and position accuracy, there is a **slight play** that could be reduced by better encapsulating the spherical gear with the top cover.

- **Battery Integration:** Integration of the battery is the next step once procurement is complete. This will include making necessary connections and incorporating the battery management system's data acquisition into the firmware for accurate battery charge state estimation.

- **Antennas Integration:** Due to limitations in firmware's node capacity, the antennas' motors have not been tested on the robot. The next step involves configuring a **buck converter** to supply the servomotors with 8 V to ensure proper operation.
- **Face Animations Improvement:** Currently, only thirteen animations corresponding to four emotions have been developed. Future work could involve creating a **spritesheet system for facial expressions** based on Plutchik's wheel, allowing for emotional states to be directly translated into dynamic facial animations, improving animated transitions scalability.
- **Thermal Analysis:** Empirical testing of the robot at various workloads, particularly focusing on the NVIDIA Jetson TX2i, could **thermally validate the robot design**. Monitoring temperatures at critical points using the built-in sensors in the servomotors could identify further design optimization opportunities.
- **Additional Modules Design:** New modules could be designed to expand the robot's capabilities, adding versatility and functionality.
- **Higher Quality Manufacturing:** The design presented in this work could benefit from higher-quality 3D printing and the use of more professional materials. **Technical drawings** may be needed for components that will be externally manufactured.
- **Assembly Manual:** A detailed user-oriented assembly manual could be beneficial, especially if more similar robots are to be manufactured.
- **Transport Solution:** Given the robot's intended use at various events, a custom, **internally-foamed suitcase** would protect the robot during transport.

### 8.2.2. Firmware and Software Enhancements

- **Arduino Microcontroller Enhancement:** Upgrading from the Arduino Mega 2560 to the **Arduino Giga R1 WiFi** [122] could overcome current dynamic memory limitations, potentially making the robot capable of running all the firmware nodes and more responsive.
- **Firmware Development for Additional Components:** Integrating firmware for components like the IMU, NFC sensor, gas detection sensors, and others is a priority. This will ensure full functionality and improve the system current capabilities.
- **Arduino Firmware Programming via NVIDIA Jetson TX2i:** Future improvements could include programming the Arduino directly from the NVIDIA Jetson TX2i via the robot's USB-C back panel port, eliminating the need for manual

UART connection to the Arduino. This can be implemented using the USB to TTL serial UART converter PCB already acquired, streamlining firmware updates.

- **Neck Mechanism Trajectories Programming:** Firmware could be enhanced to program the motors for optimal neck movement trajectories and **emotional state-dependent body positioning**, facilitating advanced applications development.

- **Application Development:** The hardware platform created in this work could be applied to various applications, such as education or personal assistance. This would require higher-level software development and seamless integration of the different software architecture modules.

- **Automatic Module Connection Detection:** The firmware could be programmed to automatically detect when a module is detected to interact in some way (such as turning on the LED ring of the ear beneath the module).

- **PCB Design and Manufacturing:** Once connections are finalized, designing a custom PCB could provide a more robust and scalable solution than the current manual implementation.

- **LDR Firmware Optimization:** The current LDR sensor firmware lacks responsiveness. Further investigation and potential sensor replacement could improve performance.

- **Firmware Improvements:** Optimization of the firmware to communicate only the changed variables could reduce bandwidth usage and improve efficiency.

- **Software Testing:** Formal unit, integration, and system tests are necessary to ensure that the software functions correctly as its complexity increases.

- **Software Performance Testing:** Monitoring software performance during operation can identify resource usage and optimization opportunities.

- **Firmware and Software Manual:** A developer-oriented manual would help new developers (students and researchers) understand the robot's architecture and follow best practices in code development.

### 8.2.3. Development Simulation Interface

- **URDF Creation:** Creating a URDF file is the first step in developing a digital twin of the robot, facilitating simulation and further development.

- **Gazebo[1] / Unity[2] Development Simulation Interface:** Developing a Gazebo or Unity simulation would enable the development and testing of applications without the need for physical hardware, which is particularly useful for collaborative projects such as this one where multiple students and researchers might be progressing on different work lines.

[1] It is a powerful robot simulation tool that allows for testing and development of robotics algorithms in realistic environments.
[2] It is a versatile and powerful real-time 3D development platform used for creating and operating interactive, real-time content such as games, simulations, and visualizations.

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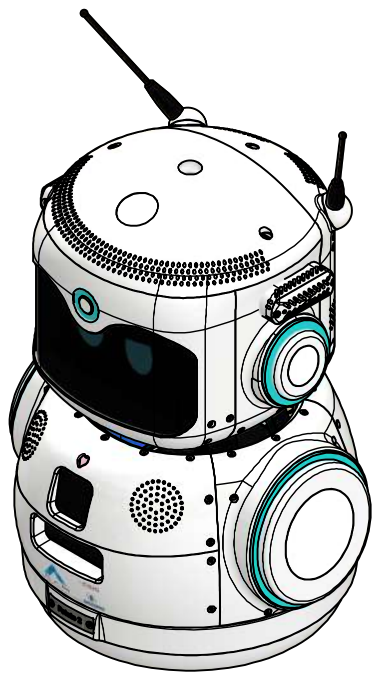
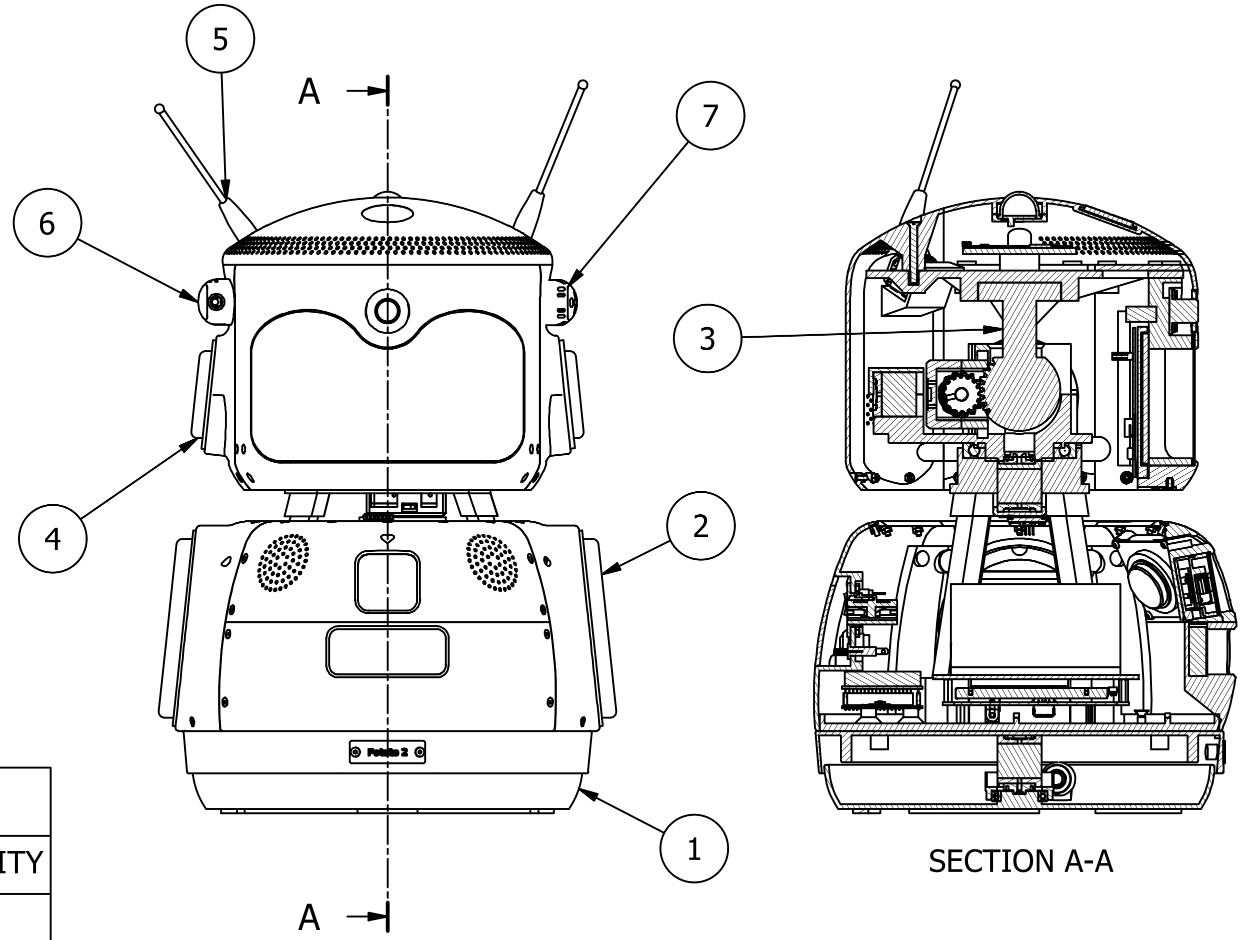
Appendix A

# Social Robot Technical Drawings

The appendix presents the detailed technical drawings of the robot's main assembly and its principal sub-assemblies. These drawings provide a comprehensive overview of the structural components and the mechanical design of the robot, serving as a visual reference for the construction and assembly processes. The following technical drawings are included:

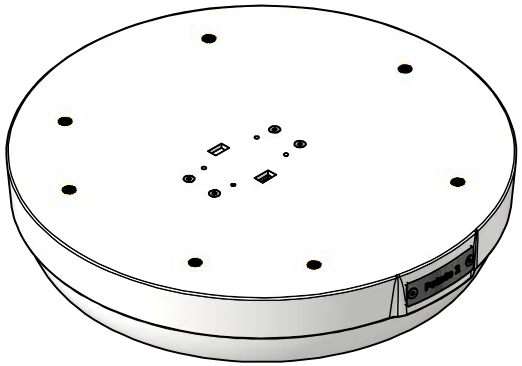
- **DRAWING 1.00:** POTATO 2
- **DRAWING 1.01:** BASE
- **DRAWING 1.02:** BODY
- **DRAWING 1.03:** NECK MECHANISM
- **DRAWING 1.04:** HEAD
- **DRAWING 1.05:** ANTENNA
- **DRAWING 1.06:** FLASHLIGHT MODULE
- **DRAWING 1.07:** GAS SENSOR MODULE

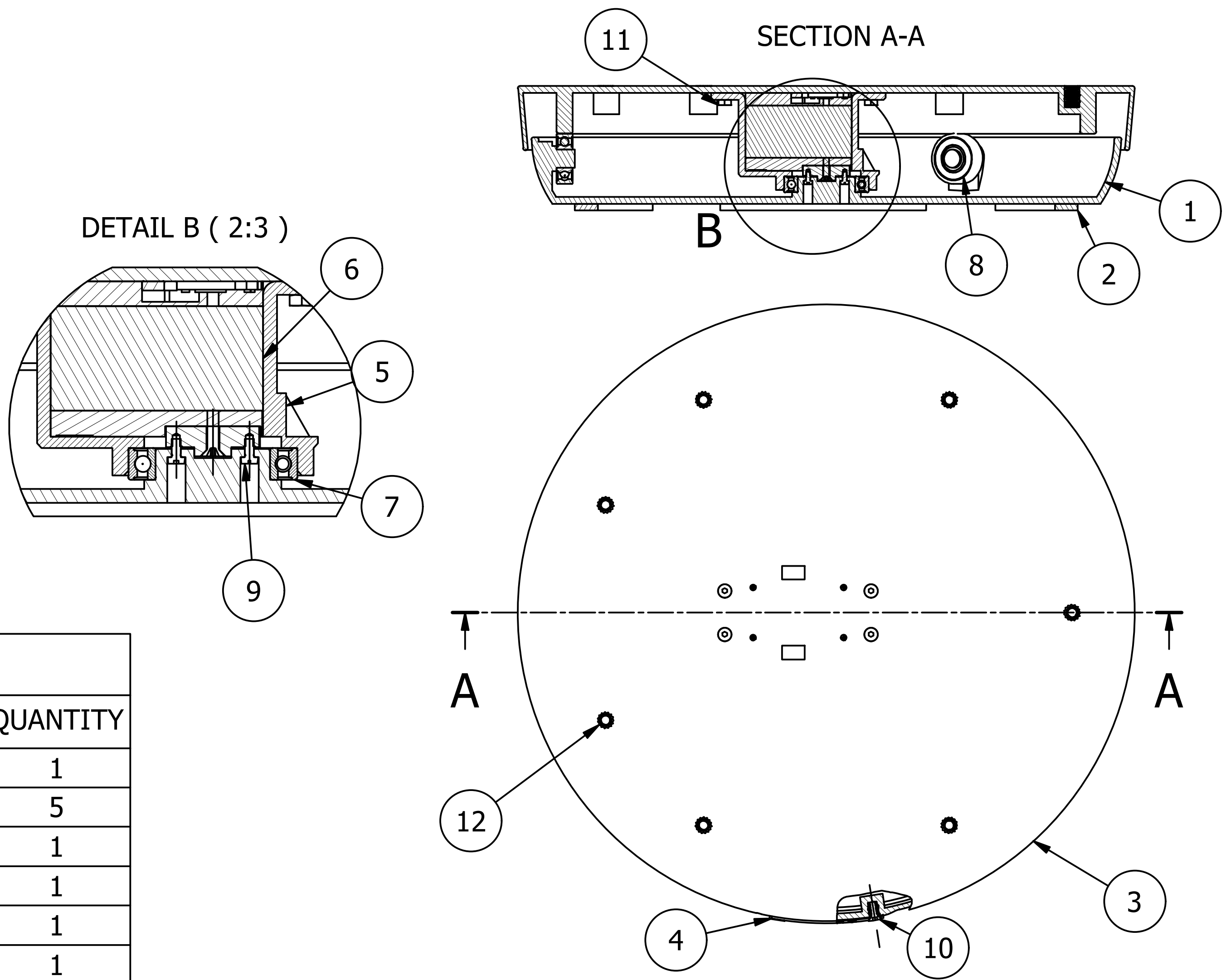





| PARTS LIST | | | |
|---|---|---|---|
| ELEMENT Nº | CODE | DESCRIPTION | QUANTITY |
| 1 | P-101 | BASE | 1 |
| 2 | P-102 | BODY | 1 |
| 3 | P-103 | NECK MECHANISM | 1 |
| 4 | P-104 | HEAD | 1 |
| 5 | P-105 | ANTENNA | 2 |
| 6 | P-106 | FLASHLIGHT MODULE | 1 |
| 7 | P-107 | GAS SENSOR MODULE | 1 |

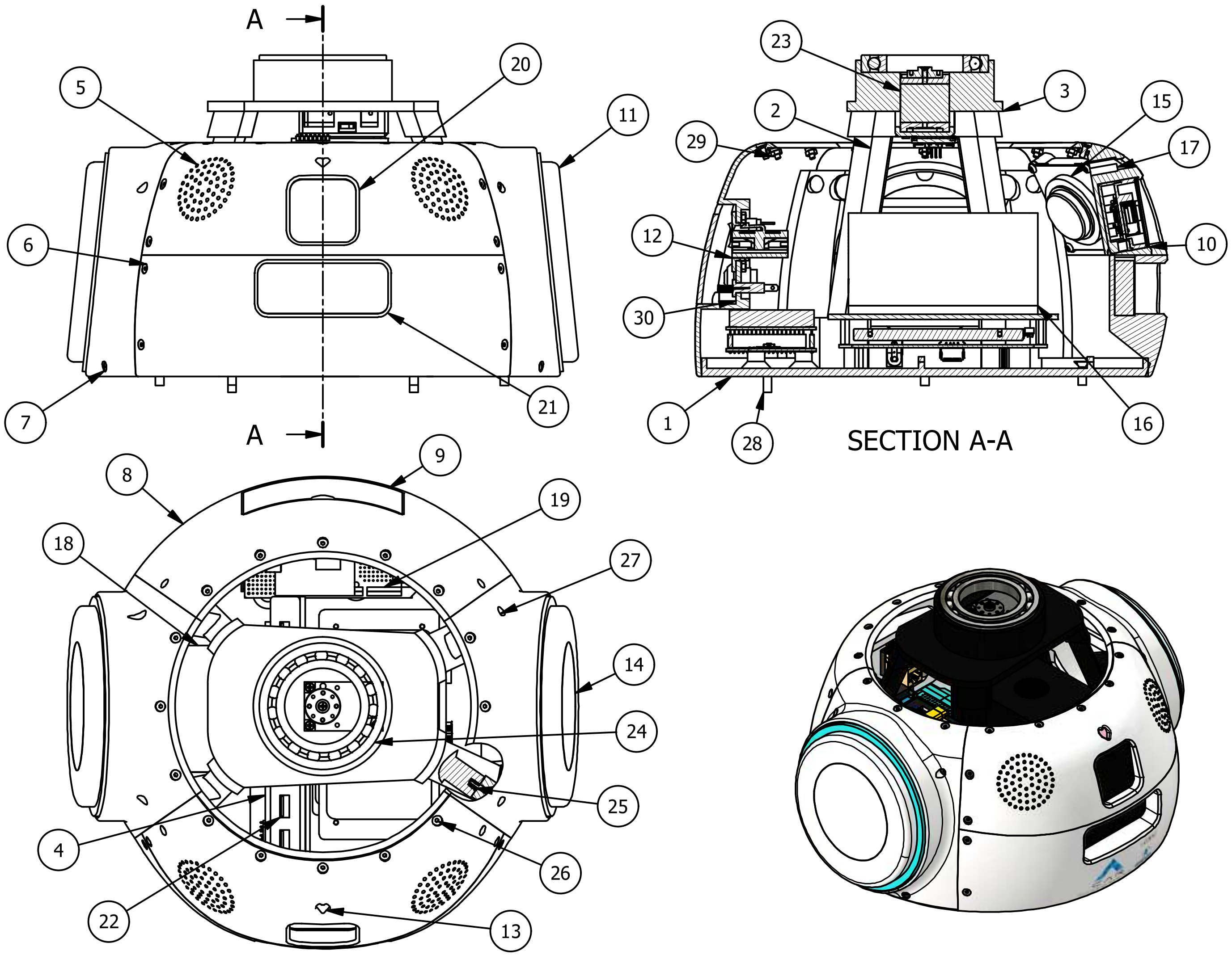
| | | | | | | |
|---|---|---|---|---|---|---|
| DATE: 12/08/2024 | SIGNATURE: | PROJECT: DESIGN, CONSTRUCTION AND PROGRAMMING OF A SOCIAL ROBOT FOR PERSONAL ASSISTANCE | | | | |
| AUTHOR: Daniel Sotelo Aguirre | | | | | | |
| INDUSTRIALES ETSII \| UPM | POLITÉCNICA | DENOMINATION: POTATO 2 | | | | WEIGHT (kg): 8.357 |
| | | PLANE Nº: 1.00 | CODE: P-100 | | A4 | SCALE: 1:5 |





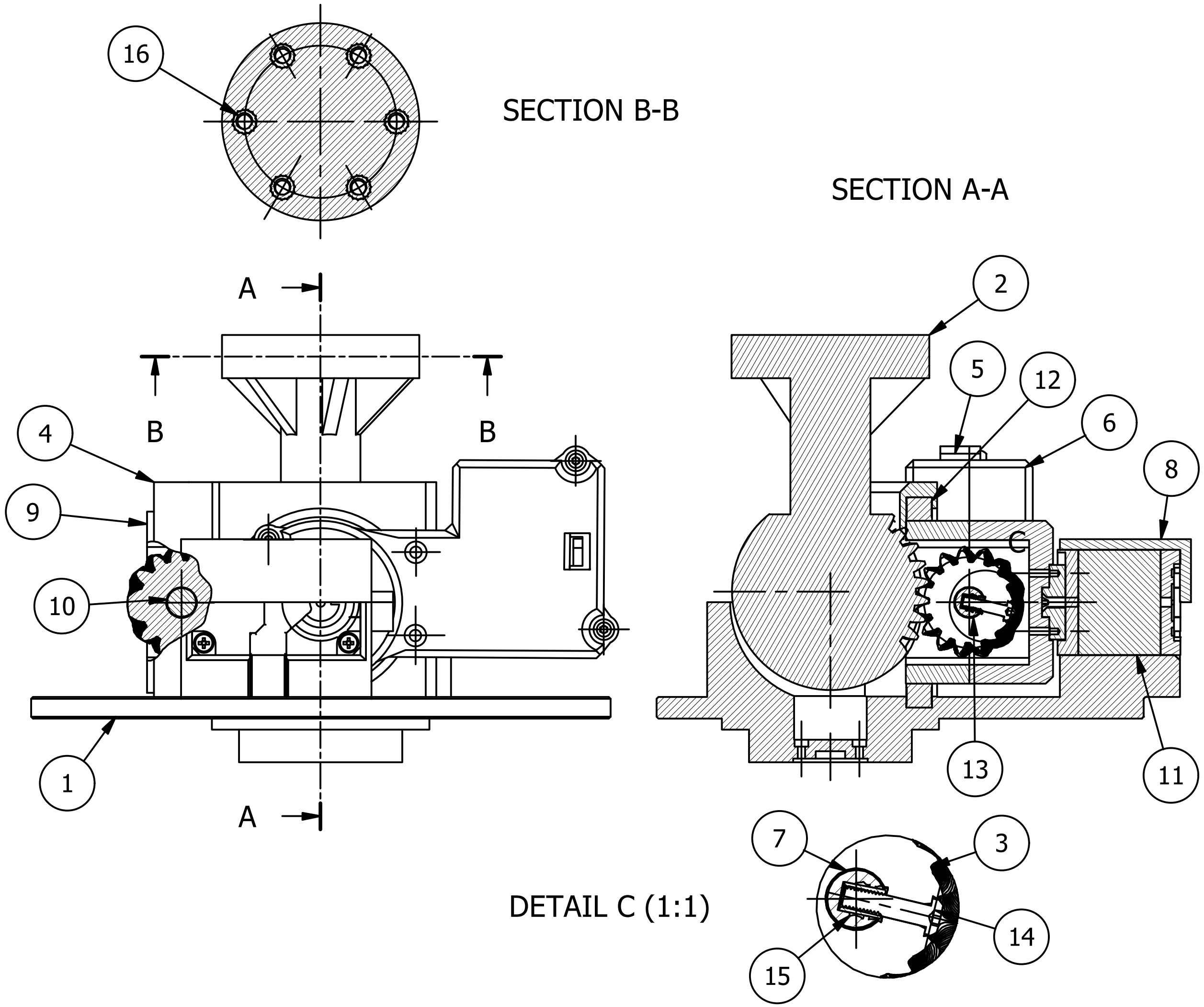

| PARTS LIST | | | |
|---|---|---|---|
| ELEMENT Nº | CODE | DESCRIPTION | QUANTITY |
| 1 | P-1011 | BOTTOM BASE | 1 |
| 2 | P-1012 | ANTI-SLIP PADS | 5 |
| 3 | P-1013 | TOP BASE | 1 |
| 4 | P-1014 | NAME PLATE | 1 |
| 5 | P-1015 | SOPORTE MOTOR | 1 |
| 6 | | DYNAMIXEL XL-430 | 1 |
| 7 | | 25x37x7 mm BEARING | 1 |
| 8 | | 8x22x7 mm BEARING | 3 |
| 9 | | M2 x 4 BOLT | 4 |
| 10 | | M3 x 8 BOLT | 6 |
| 11 | | M3 x 2.4 NUT | 4 |
| 12 | | M5 THREADED INSERT | 7 |

| | | | | | |
|---|---|---|---|---|---|
| DATE: 12/08/2024 | SIGNATURE: | PROJECT: DESIGN, CONSTRUCTION AND PROGRAMMING OF A SOCIAL ROBOT FOR PERSONAL ASSISTANCE | | | |
| AUTHOR: Daniel Sotelo Aguirre | | | | | |
| INDUSTRIALES ETSII \| UPM | POLITÉCNICA | DENOMINATION: BASE | | | WEIGHT (kg): 0.841 |
| | | PLANE Nº: 1.01 | CODE: P-101 | A4 | SCALE: 1:3 |




| PARTS LIST | | | |
|---|---|---|---|
| ELEMENT Nº | CODE | DESCRIPTION | QUANTITY |
| 1 | P-1021 | BODY SUPPORT | 1 |
| 2 | P-1022 | LEG | 4 |
| 3 | P-1023 | MECHANISM SUPPORT | 1 |
| 4 | P-1024 | USB-HUB SUPPORT | 1 |
| 5 | P-1025 | FRONT TOP PANEL | 1 |
| 6 | P-1026 | FRONT BOTTOM PANEL | 1 |
| 7 | P-1027 | LATERAL PANEL | 2 |
| 8 | P-1028 | BACK PANEL | 1 |
| 9 | P-1029 | PORTS PANEL COVER | 1 |
| 10 | P-10210 | CAMERA COVER | 1 |
| 11 | P-10211 | LATERAL COVER | 2 |
| 12 | P-10212 | PORTS PANEL | 1 |
| 13 | P-10213 | LED COVER | 3 |
| 14 | P-10214 | TACTILE PAD | 1 |
| 15 | | SPEAKER | 2 |
| 16 | | NVIDIA JETSON TX2i | 1 |
| 17 | | LED ring | 3 |
| 18 | | BATTERY | 1 |
| 19 | | ARDUINO MEGA 2560 | 1 |
| 20 | | INTEL REALSENSE D405 CAMERA | 1 |
| 21 | | LEAP MOTION CONTROLLER | 1 |
| 22 | | USB-HUB | 1 |
| 23 | | DYNAMIXEL XL-430 | 1 |
| 24 | | 45x75x10 mm BEARING | 1 |
| 25 | | M3 THREADED INSERT | 28 |
| 26 | | M3 x 8 BOLT | 36 |
| 27 | | M3 x 20 BOLT | 8 |
| 28 | | M5 x 20 BOLT | 7 |
| 29 | | M3 x 2.4 NUT | 16 |
| 30 | | MAGNET | 16 |

| | | | | | |
|---|---|---|---|---|---|
| DATE: 12/08/2024 | SIGNATURE: | PROJECT: DESIGN, CONSTRUCTION AND PROGRAMMING OF A SOCIAL ROBOT FOR PERSONAL ASSISTANCE | | | |
| AUTHOR: Daniel Sotelo Aguirre | | | | | |
| INDUSTRIALES ETSII \| UPM | POLITÉCNICA | DENOMINATION: BODY | | | WEIGHT (kg): 4.51 |
| | | PLANE Nº: 1.02 | CODE: P-102 | A4 | SCALE: 1:4 |

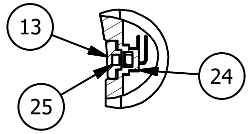


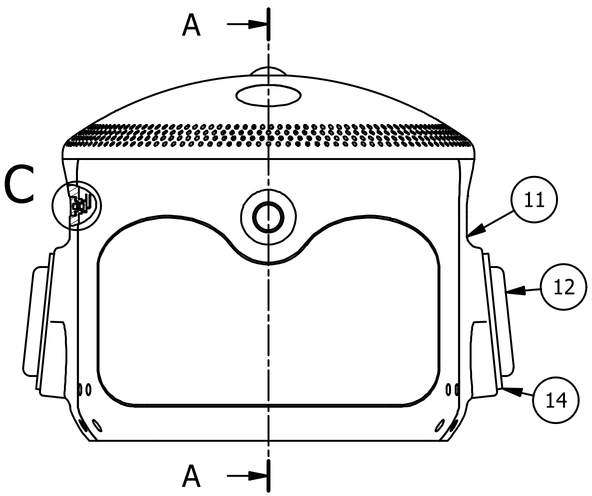

PARTS LIST

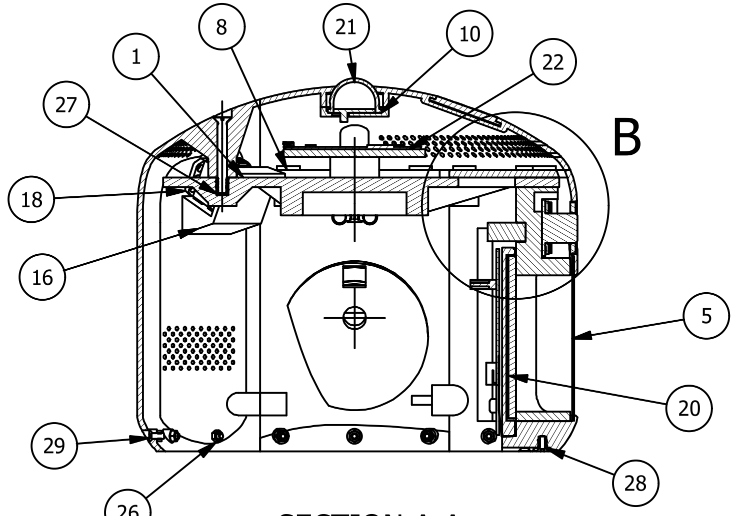
| ELEMENT Nº | CODE | DESCRIPTION | QUANTITY |
|---|---|---|---|
| 1 | P-1031 | BOTTOM BASE | 1 |
| 2 | P-1032 | SPHERICAL GEAR | 1 |
| 3 | P-1033 | SHERICAL PINION | 2 |
| 4 | P-1034 | GEAR COVER | 1 |
| 5 | P-1035 | MOTOR PINION CASE | 1 |
| 6 | P-1036 | MOTOR PINION COVER | 1 |
| 7 | P-1037 | MOTOR PINION AXIS | 1 |
| 8 | P-1038 | MOTOR COVER | 1 |
| 9 | P-1039 | SUPPORT PINION CASE | 1 |
| 10 | P-10310 | SUPPORT PINION AXIS | 1 |
| 11 | | DYNAMIXEL XL-430 | 2 |
| 12 | | 45x58x7 mm BEARING | 2 |
| 13 | | 8x12x3.5 mm BEARING | 3 |
| 14 | | M3 x 12 BOLT | 5 |
| 15 | | M3 THREADED INSERT | 1 |
| 16 | | M5 THREADED INSERT | 6 |

| | | |
|---|---|---|
| DATE: 12/08/2024 | SIGNATURE: | PROJECT: DESIGN, CONSTRUCTION AND PROGRAMMING OF A SOCIAL ROBOT FOR PERSONAL ASSISTANCE |
| AUTHOR: Daniel Sotelo Aguirre | | |
| INDUSTRIALES ETSII \| UPM | POLITÉCNICA | DENOMINATION: NECK MECHANISM — WEIGHT (kg): 0.741 |
| | | PLANE Nº: 1.03 — CODE: P-103 — A4 — SCALE: 1:2 |

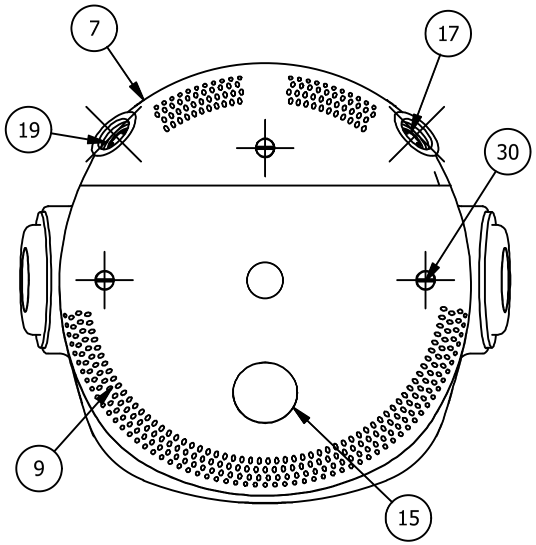
DETAIL C (1:2)

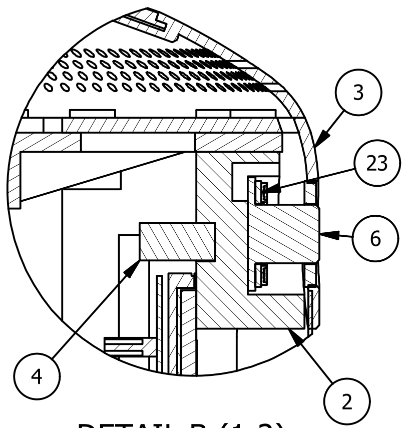


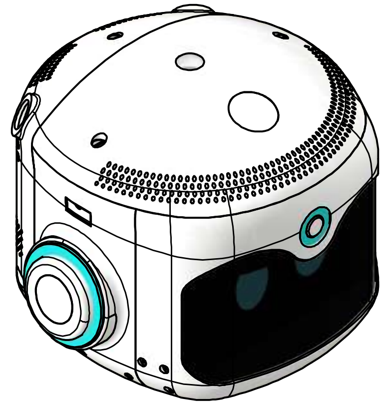




SECTION A-A



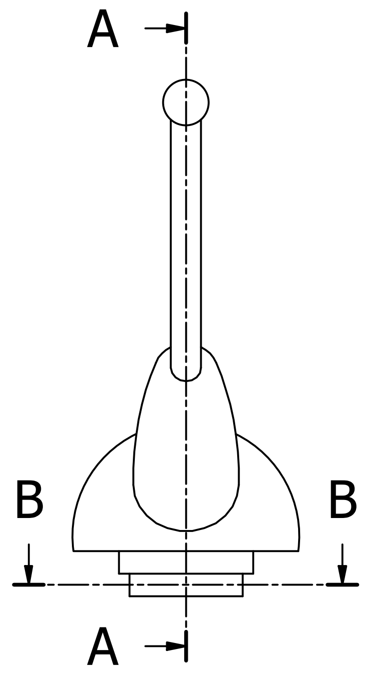

DETAIL B (1:2)

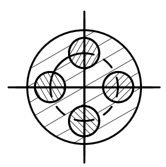


PARTS LIST

| ELEMENT Nº | CODE | DESCRIPTION | QUANTITY |
|---|---|---|---|
| 1 | P-1041 | TOP SUPPORT BASE | 1 |
| 2 | P-1042 | LCD DISPLAY FRAME | 1 |
| 3 | P-1043 | FRONT PANEL | 1 |
| 4 | P-1044 | LCD DISPLAY LOCK | 1 |
| 5 | P-1045 | PVC PANEL | 1 |
| 6 | P-1046 | FRONT LED RING SUPPORT | 1 |
| 7 | P-1047 | BACK PANEL | 1 |
| 8 | P-1048 | MICROPHONE SUPPORT | 1 |
| 9 | P-1049 | TOP PANEL | 1 |
| 10 | P-10410 | LDR SUPPORT | 1 |
| 11 | P-10411 | LATERAL PANEL | 2 |
| 12 | P-10412 | EAR COVER | 2 |
| 13 | P-10413 | PIN PORT COVER | 2 |
| 14 | P-10414 | LED COVER | 3 |
| 15 | P-10415 | TACTILE PAD | 3 |
| 16 | P-10416 | MOTOR SUPPORT | 2 |
| 17 | P-10417 | ANTENNA MOTOR LINK | 2 |
| 18 | | DYNAMIXEL XL-320 | 2 |
| 19 | | 15x24x5 mm BEARING | 2 |
| 20 | | LCD DISPLAY | 1 |
| 21 | | LDR SENSOR | 1 |
| 22 | | MICROPHONE ARRAY | 1 |
| 23 | | LED RING | 3 |
| 24 | | MALE 6-PIN CONNECTOR | 2 |
| 25 | | MAGNET | 24 |
| 26 | | M3x2.4 NUT | 18 |
| 27 | | M5 THREADED INSERT | 13 |
| 28 | | M3 THREADED INSERT | 21 |
| 29 | | M3 x 8 BOLT | 34 |
| 30 | | M5 x 20 BOLT | 16 |

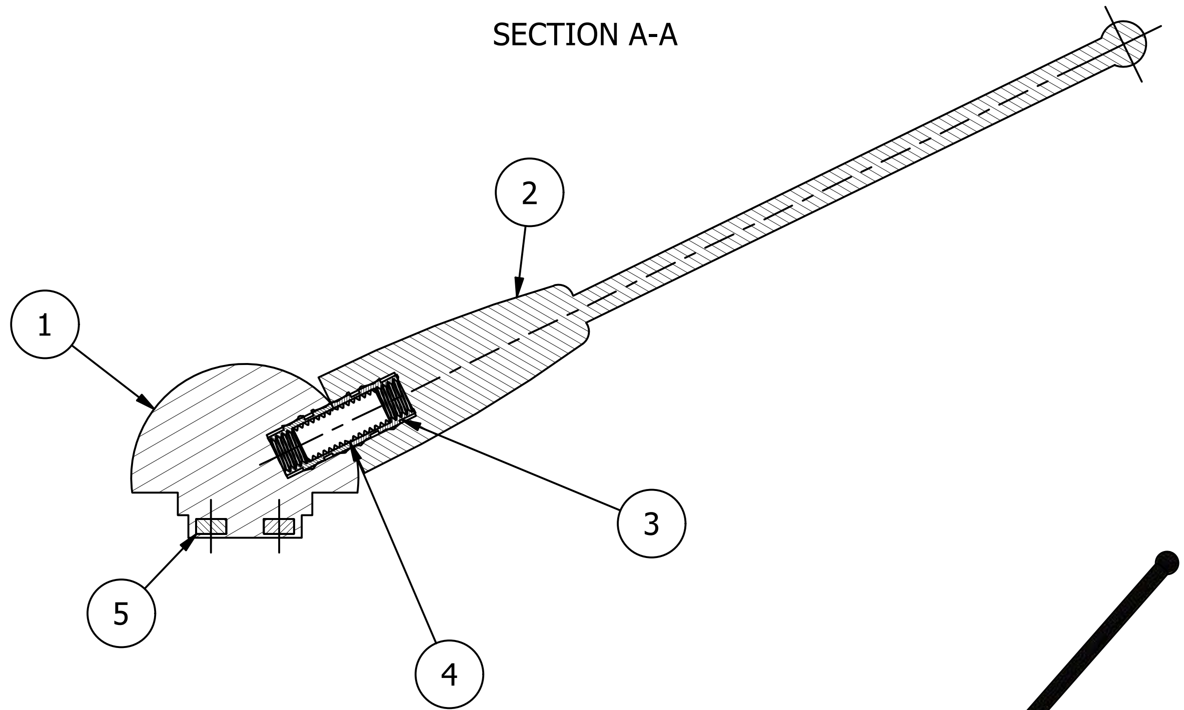
| | | | | |
|---|---|---|---|---|
| DATE: 12/08/2024 | SIGNATURE: | PROJECT: DESIGN, CONSTRUCTION AND PROGRAMMING OF A SOCIAL ROBOT FOR PERSONAL ASSISTANCE | | |
| AUTHOR: Daniel Sotelo Aguirre | | | | |
| INDUSTRIALES ETSII \| UPM | POLITÉCNICA | DENOMINATION: HEAD | | WEIGHT (kg): 2.103 |
| | | PLANE Nº: 1.04 | CODE: P-104 | A4 \| SCALE: 1:4 |



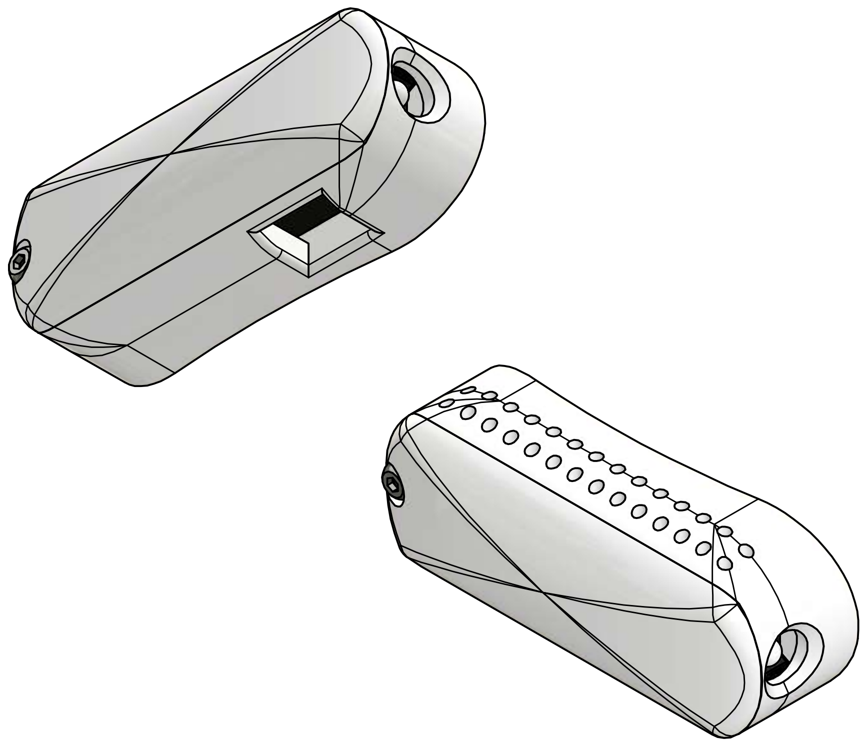
SECTION B-B

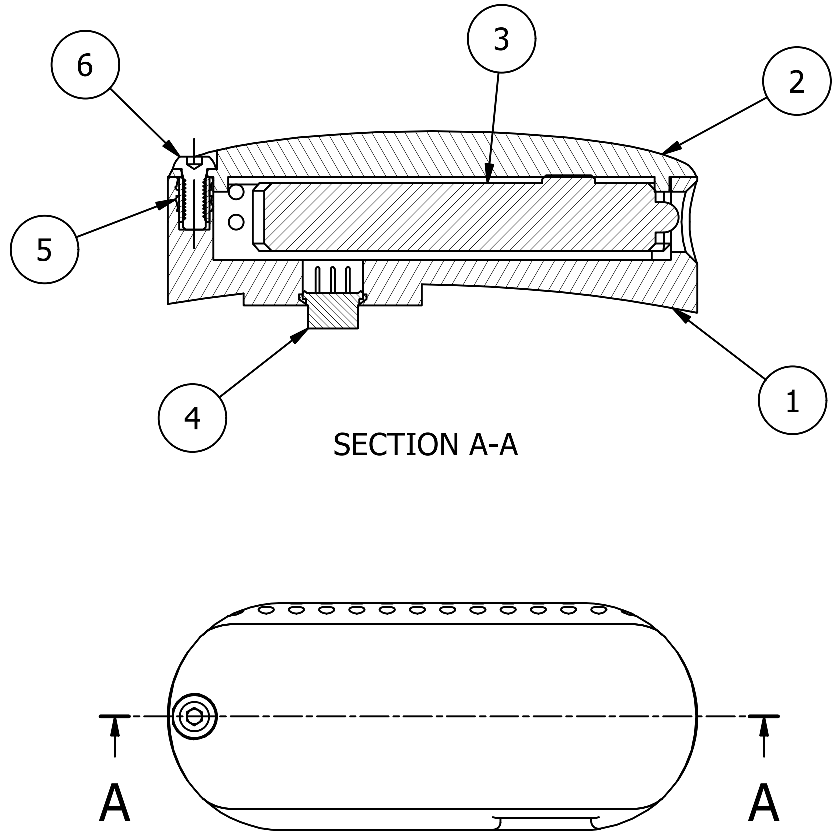
SECTION A-A




| PARTS LIST | | | |
|---|---|---|---|
| ELEMENT Nº | CODE | DESCRIPTION | QUANTITY |
| 1 | P-1051 | SPHERICAL BASE | 1 |
| 2 | P-1052 | ANTENNA TIP | 1 |
| 3 | | M5 THREADED INSERT | 2 |
| 4 | | STUD BOLT | 1 |
| 5 | | MAGNET | 4 |

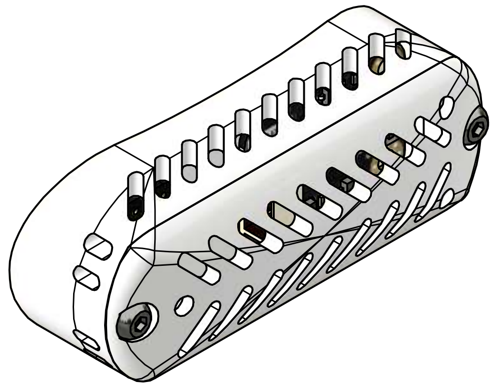
| | | |
|---|---|---|
| DATE: 12/08/2024 | SIGNATURE: | PROJECT: DESIGN, CONSTRUCTION AND PROGRAMMING OF A SOCIAL ROBOT FOR PERSONAL ASSISTANCE |
| AUTHOR: Daniel Sotelo Aguirre | | |
| INDUSTRIALES ETSII \| UPM / POLITÉCNICA | DENOMINATION: ANTENNA | WEIGHT (kg): 0.023 |
| PLANE Nº: 1.05 | CODE: P-105 | A4 · SCALE: 1:1 |

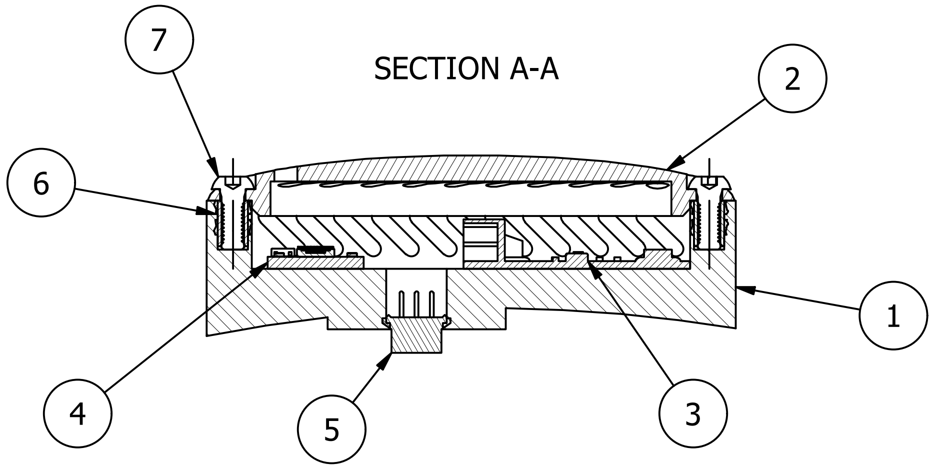


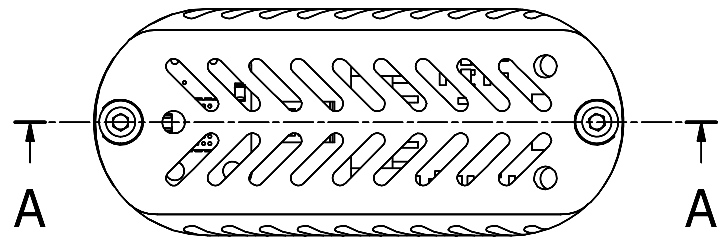



| PARTS LIST | | | |
|---|---|---|---|
| ELEMENT Nº | CODE | DESCRIPTION | QUANTITY |
| 1 | P-1061 | MODULE BODY | 1 |
| 2 | P-1062 | MODULE COVER | 1 |
| 3 | | FLASHLIGHT | 1 |
| 4 | | FEMALE 6-PIN CONNECTOR | 1 |
| 5 | | M3 THREADED INSERT | 1 |
| 6 | | M3 x 8 BOLT | 1 |

| | | |
|---|---|---|
| DATE: 12/08/2024 | SIGNATURE: | PROJECT: DESIGN, CONSTRUCTION AND PROGRAMMING OF A SOCIAL ROBOT FOR PERSONAL ASSISTANCE |
| AUTHOR: Daniel Sotelo Aguirre | | |
| INDUSTRIALES ETSII \| UPM | POLITÉCNICA | DENOMINATION: FLASHLIGHT MODULE — WEIGHT (kg): 0.048 |
| | | PLANE Nº: 1.06 — CODE: P-106 — A4 — SCALE: 1:1 |






| PARTS LIST | | | |
|---|---|---|---|
| ELEMENT Nº | CODE | DESCRIPTION | QUANTITY |
| 1 | P-1071 | MODULE BODY | 1 |
| 2 | P-1072 | MODULE COVER | 1 |
| 3 | | AIR QUALITY SENSOR | 1 |
| 4 | | HAZARDOUS GAS SENSOR | 1 |
| 5 | | FEMALE 6-PIN CONNECTOR | 1 |
| 6 | | M3 THREADED INSERT | 2 |
| 7 | | M3 x 8 BOLT | 2 |

| | | |
|---|---|---|
| DATE: 12/08/2024 | SIGNATURE: | PROJECT: DESIGN, CONSTRUCTION AND PROGRAMMING OF A SOCIAL ROBOT FOR PERSONAL ASSISTANCE |
| AUTHOR: Daniel Sotelo Aguirre | | |
| INDUSTRIALES ETSII \| UPM | POLITÉCNICA | DENOMINATION: GAS SENSOR MODULE |
| WEIGHT (kg): 0.025 | | |
| PLANE Nº: 1.07 | CODE: P-107 | A4 |
| SCALE: 1:1 | | |

Appendix B

# Applications and Impact Analysis

## B.1. Applications

The field of social robotics is expanding rapidly, driven by the increasing need for robots that can interact naturally and effectively with humans in various settings. The social robot developed in this Master's Thesis is designed to be highly versatile, with potential applications across multiple domains. These include **personal assistance** for the **elderly and individuals with disabilities**, where the robot can provide **companionship**, remind users of **medication schedules**, and assist with **daily tasks**. In **educational environments**, the robot can serve as an interactive **learning tool**, engaging through NLP and emotional responses. Additionally, the robot can be deployed in **customer service roles**, where it can enhance user experience through personalized interactions, and in healthcare settings, where it can **support patients** by monitoring their well-being and providing real-time feedback to caregivers.

## B.2. Impact Analysis

Developing and deploying this social robot involves **significant economic investment** in terms of research, development, manufacturing, and maintenance. However, the robot's ability to perform tasks traditionally carried out by humans, such as caregiving, customer service, and education, can lead to **long-term cost savings and increased efficiency**. The robot's modular design allows for customization and scalability, which can reduce costs over time by minimizing the need for multiple specialized robots.

The social impact of this robot is profound. By providing companionship and assistance to the elderly, individuals with disabilities, and young people with chronic conditions like diabetes, the robot **can significantly improve quality of life**. It **reduces loneliness**, promotes **independence**, and ensures better **adherence to health management routines**. In educational settings, the robot's interactive features can foster

**engagement and motivation among students**, leading to better learning outcomes. However, it is important to consider the **ethical implications** of automation, particularly the potential displacement of jobs. While the robot can perform tasks traditionally done by humans, it is essential to balance this with the creation of new job opportunities in robot maintenance, programming, and AI development.

A key legal consideration for the social robot is **data privacy**. To comply with regulations like the General Data Protection Regulation (GDPR), the robot will process and store user data **locally**, avoiding cloud-based systems and reducing security risks. This ensures senstitive information, such as health data, is kept secure. The system in the future could include **encryption** and **user consent** mechanisms, giving users control over their data. By adhering to **data minimization** principles, the robot will collect only necessary information, ensuring compliance with privacy laws while maintaining trust in healthcare and personal settings.

The environmental impact of the robot is a key consideration, particularly in terms of material usage and energy consumption. Constructed primarily from PETG plastic and metals, the robot's **materials contribute to its carbon footprint** through extraction, processing, and disposal. Its electronics also add to its impact. To mitigate these effects, **future iterations** should explore more **sustainable materials** and energy-efficient technologies. A comprehensive life cycle assessment would help identify ways to reduce the robot's environmental footprint across its production, use, and disposal stages.

## B.3. Contribution to Sustainable Development Goals

The social robot developed in this project contributes to several Sustainable Development Goals (SDGs), as highlighted below and indicated in Figure B.1.

- **SDG 3 - Good Health and Well-Being:** The robot enhances the quality of healthcare by providing personalized assistance and monitoring, particularly for the elderly, individuals with disabilities, and young people with chronic conditions like diabetes, contributing to better health outcomes.
- **SDG 4 - Quality Education:** By serving as an interactive educational tool, the robot supports inclusive and equitable quality education, promoting lifelong learning opportunities for all.
- **SDG 8 - Decent Work and Economic Growth:** The robot's development and deployment create new job opportunities in the fields of robotics, AI, and healthcare technology, contributing to economic growth and innovation.
- **SDG 9 - Industry, Innovation, and Infrastructure:** The project advances technological innovation by integrating cutting-edge AI and sensor technologies into a practical and socially beneficial application.


**Figure B.1.** SDGs to which the project contributes.

- **SDG 12 - Responsible Consumption and Production:** Efforts to minimize the robot's environmental impact align with responsible consumption and production practices, particularly through the exploration of sustainable materials and energy-efficient design in future iterations.

Appendix C

# Temporal Planning and Budget

## C.1. Work Breakdown Structure (WBS)

The Work Breakdown Structure (WBS) shown in Figure C.1 provides a comprehensive overview of the project's phases, outlining the key tasks and milestones required to develop the social robot.

## C.2. Planning

This section details the project timeline corresponding to the work packages defined in the WBS using a Gantt chart. The Gantt chart is shown in Figure C.2.

## C.3. Budget

This budget section outlines the financial resources required for the project. It includes a breakdown of costs associated with materials, equipment, and personnel.

### C.3.1. Material Costs

Table C.1 summarizes the expenses for materials used in the project, including materials, electronics, and other components necessary for the robot's construction.

### C.3.2. Equipment Amortization Costs

The amortization costs of equipment used during the project, such as the 3D printers and the soldering station, are calculated distributing their initial costs over the useful life of these tools, as summarized in Table C.2.

### C.3.3. Personnel Costs

Table C.3 accounts for the labor costs, including the time and expertise of the team members involved in the project, calculated based on their respective roles and hourly rates.

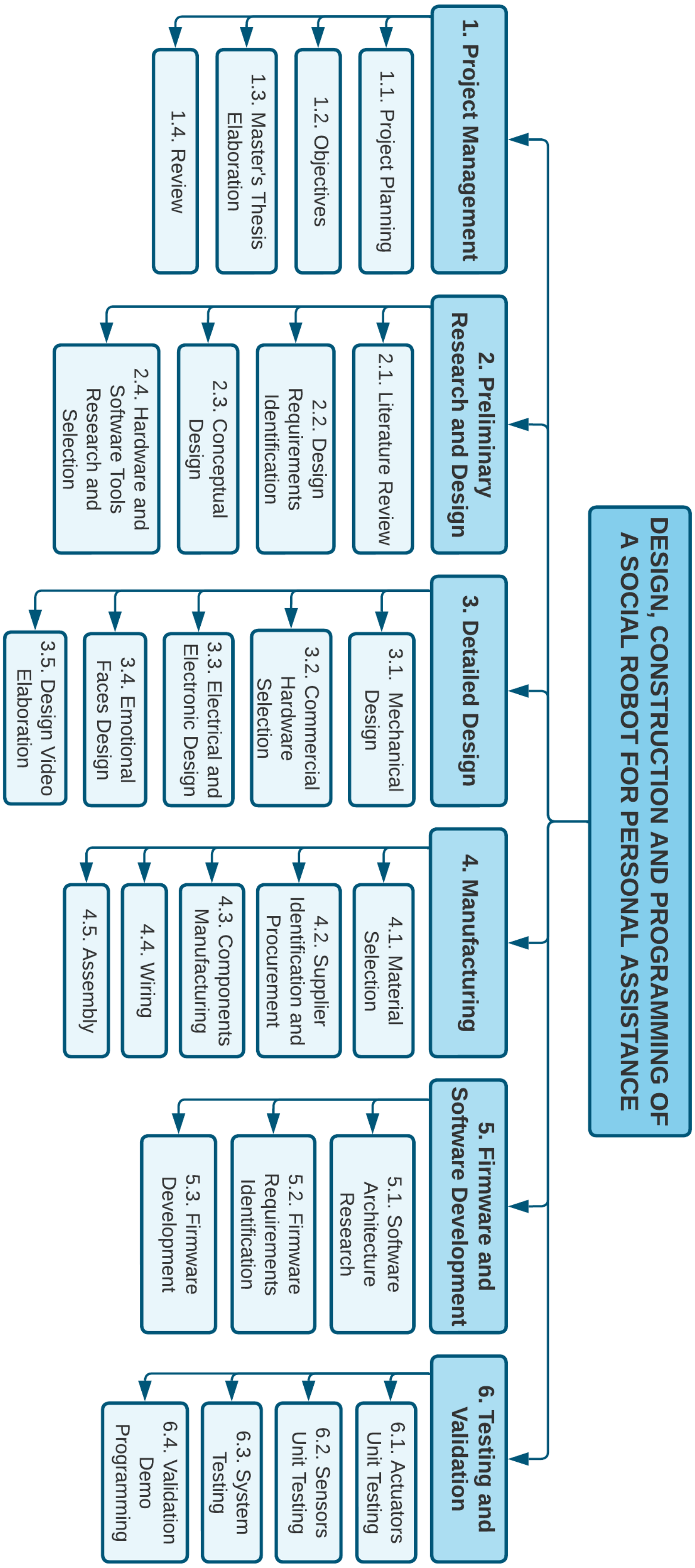



**Figure C.1.** Project WBS.

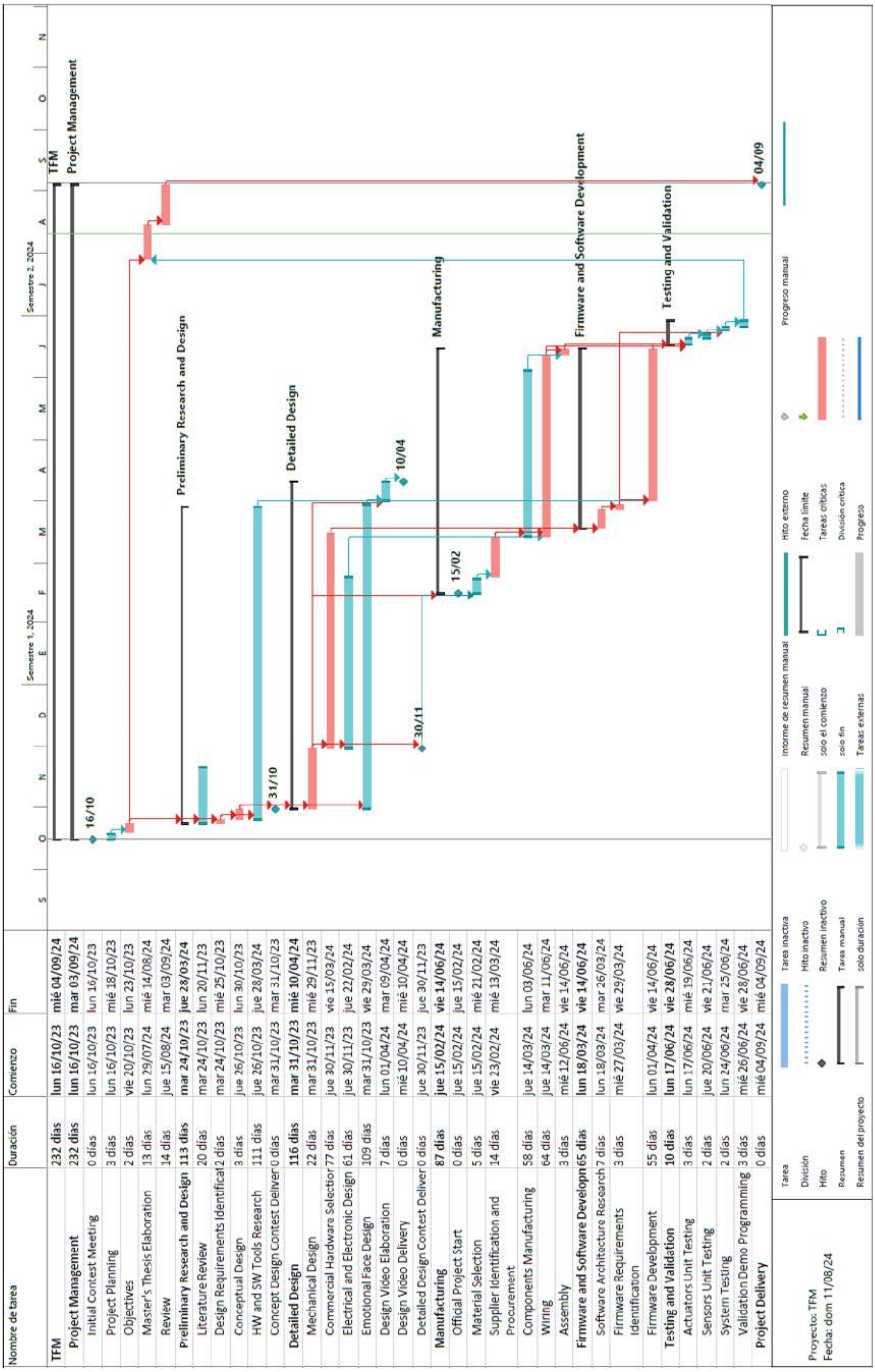



**Figure C.2.** Project Gantt Chart.

| Concept | Units | Unit Price | Total Price |
|---|---|---|---|
| **Construction Materials** | | | **506,31 €** |
| PETG Filament | 5 | 50,19 € | 250,95 € |
| ABS Filament | 1 | 43,10 € | 43,10 € |
| PVC panel | 1 | 3,84 € | 3,84 € |
| Elastic Textile Mesh | 1 | 9,01 € | 9,01 € |
| Neodymium Magnets | 6 | 17,42 € | 104,52 € |
| Silicone Sheet | 1 | 13,99 € | 13,99 € |
| Copper Sheet | 1 | 11,87 € | 11,87 € |
| Roller Bearings | 9 | 7,67 € | 69,03 € |
| Polystyrene Panel | 1 | 1,36 € | 1,36 € |
| Anti-Slip Foam Adhesives | 1 | 12,89 € | 12,89 € |
| **Post-Processing Materials** | | | **80,32 €** |
| Priming Spray | 1 | 14,00 € | 14,00 € |
| Varnish Spray | 1 | 7,50 € | 7,50 € |
| Waterslide Decal Paper | 1 | 18,99 € | 18,99 € |
| Paint Spray | 3 | 6,59 € | 19,77 € |
| Sanding Paper | 1 | 12,86 € | 12,86 € |
| Cyanoacrylate | 1 | 7,20 € | 7,20 € |
| **Electrical Assembly Materials** | | | **493,77 €** |
| Fuse + Fuse Holder | 1 | 0,44 € | 0,44 € |
| Color Cables | 1 | 32,49 € | 32,49 € |
| Battery | 1 | 175,93 € | 175,93 € |
| Battery Charger | 1 | 105,00 € | 105,00 € |
| Other Cables | 1 | 43,20 € | 43,20 € |
| Ports and Connectors | 1 | 89,75 € | 89,75 € |
| Heat-Shrink Tube | 1 | 7,99 € | 7,99 € |
| Crimping Components | 1 | 38,97 € | 38,97 € |
| **Total Material Cost** | | | **3.477,56 €** |

| Concept | Units | Unit Price | Total Price |
|---|---|---|---|
| **Electronic Hardware** | | | **2.277,65 €** |
| SSD Shield | 1 | 31,00 € | 31,00 € |
| SSD 1TB | 1 | 210,41 € | 210,41 € |
| Jetson TX2 + Heatsink + Jetson Shield | 1 | 673,00 € | 673,00 € |
| Leap Motion Controller | 1 | 134,20 € | 134,20 € |
| Intel RealSense D405 Camera | 1 | 279,28 € | 279,28 € |
| LED Rings | 2 | 22,08 € | 44,16 € |
| USB Hub | 1 | 64,80 € | 64,80 € |
| Speakers + Audio Amplifier | 1 | 50,40 € | 50,40 € |
| LDR Sensor | 1 | 10,47 € | 10,47 € |
| IMU | 1 | 30,29 € | 30,29 € |
| Adafruit MPR121 | 1 | 22,76 € | 22,76 € |
| XL-320 Motor | 2 | 26,00 € | 52,00 € |
| XL-430 Motor | 4 | 48,27 € | 193,08 € |
| Wi-Fi Antenna | 1 | 10,45 € | 10,45 € |
| Arduino Mega + Proto Shield | 1 | 48,40 € | 48,40 € |
| Dynamixel Shield | 1 | 24,27 € | 24,27 € |
| RTC | 1 | 13,59 € | 13,59 € |
| NFC | 1 | 38,49 € | 38,49 € |
| Microphone Array | 1 | 64,00 € | 64,00 € |
| Wattmeter | 1 | 6,42 € | 6,42 € |
| Serial UART Converter PCB | 1 | 16,55 € | 16,55 € |
| Flashlight + MOSFET | 1 | 17,77 € | 17,77 € |
| Air Quality Sensor | 1 | 18,59 € | 18,59 € |
| Hazardous Gas Detector | 1 | 9,21 € | 9,21 € |
| Buck Converter | 2 | 25,23 € | 50,46 € |
| LCD Display | 1 | 163,60 € | 163,60 € |
| **Fasteners** | | | **119,51 €** |
| M3 Threaded Inserts | 1 | 20,07 € | 20,07 € |
| M5 Threaded Inserts | 1 | 39,37 € | 39,37 € |
| Bolts | 1 | 46,52 € | 46,52 € |
| Washers | 1 | 2,13 € | 2,13 € |
| Nuts | 1 | 11,42 € | 11,42 € |

**Table C.1.** Project Material Costs.

| Concept | Total Cost | Years | Amortization Cost / Year | Use | Amortization Cost |
|---|---|---|---|---|---|
| Prusa MK3 3D Printer | 999,00 € | 5 | 199,80 € | 6 months | 99,90 € |
| Laser Cutting Machine | 5.070,00 € | 10 | 507,00 € | 1 day | 1,39 € |
| Welding Station | 62,99 € | 10 | 6,30 € | 6 months | 3,15 € |
| Painting Personal Protective Equipment | 24,99 € | 3 | 8,33 € | 2 months | 1,39 € |
| Toolbox | 65,30 € | 10 | 6,53 € | 6 months | 3,27 € |
| Hot Glue Gun | 7,85 € | 3 | 2,62 € | 6 months | 1,31 € |
| Heat Gun | 29,99 € | 5 | 6,00 € | 6 months | 3,00 € |
| Dremel Multi-Tool | 35,40 € | 5 | 7,08 € | 6 months | 3,54 € |
| Laptop | 1.250,00 € | 5 | 250,00 € | 232 days | 158,90 € |
| **Total Amortization Cost** | | | | | **275,84 €** |

**Table C.2.** Project Amortization Costs.

| Concept | Hour Cost | Hours | Cost |
|---|---|---|---|
| Project Author | 7,00 € | 460 | 3.220,00 € |
| Project Director 1 | 40,00 € | 40 | 1.600,00 € |
| Predoctoral Researcher | 20,00 € | 100 | 2.000,00 € |
| **Total Personnel Cost** | | | **6.820,00 €** |

**Table C.3.** Project Personnel Costs.

### C.3.4. Total Cost

Table C.4 shows the total project costs calculation, combining material, equipment, and personnel expenses to give a complete financial overview of the project's expenditure.

| Totals | Cost |
|---|---|
| Total Material Cost | 3.477,56 € |
| Total Amortization Cost | 275,84 € |
| Total Personnel Cost | 6.820,00 € |
| **TOTAL PROJECT COST** | **10.573,40 €** |

**Table C.4.** Project Total Cost.

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