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:** - Arduino Mega 2560 - NVIDIA Jetson TX2i (processing unit) - 7" LCD display - 1 TB Solid State Disk (SSD) - 4-microphone array and speakers - USB hub - Lithium-ion battery - External connection ports and power switch - Actuators: Motors and LEDs - Sensors: Tactile and Light Dependent Resistor (LDR) **Optional components:** - Leap Motion Controller - Intel RealSense D405 camera - Samsung Galaxy A8 tablet
Minimum functionalities	The users must be able to: - Caress the robot - Interact with at least one robot mobile part - Talk with the robot (audio input and output) - 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].

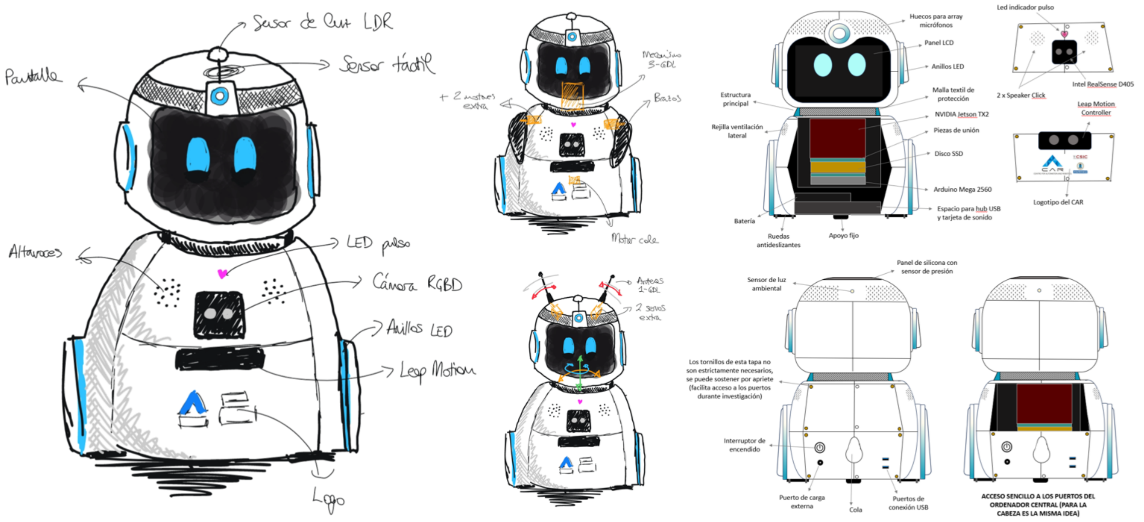


Figure 4.1. Examples of sketches and ideas from the design process.

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.

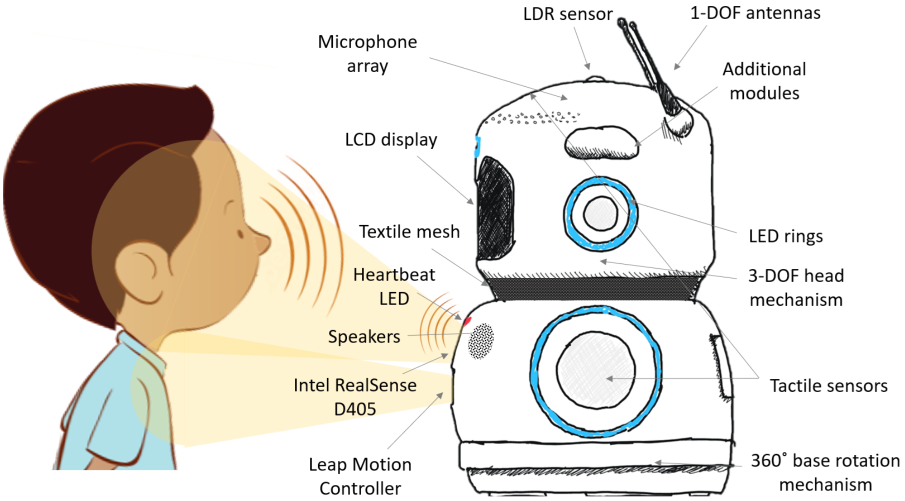


Figure 4.2. Concept design HRI.

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.

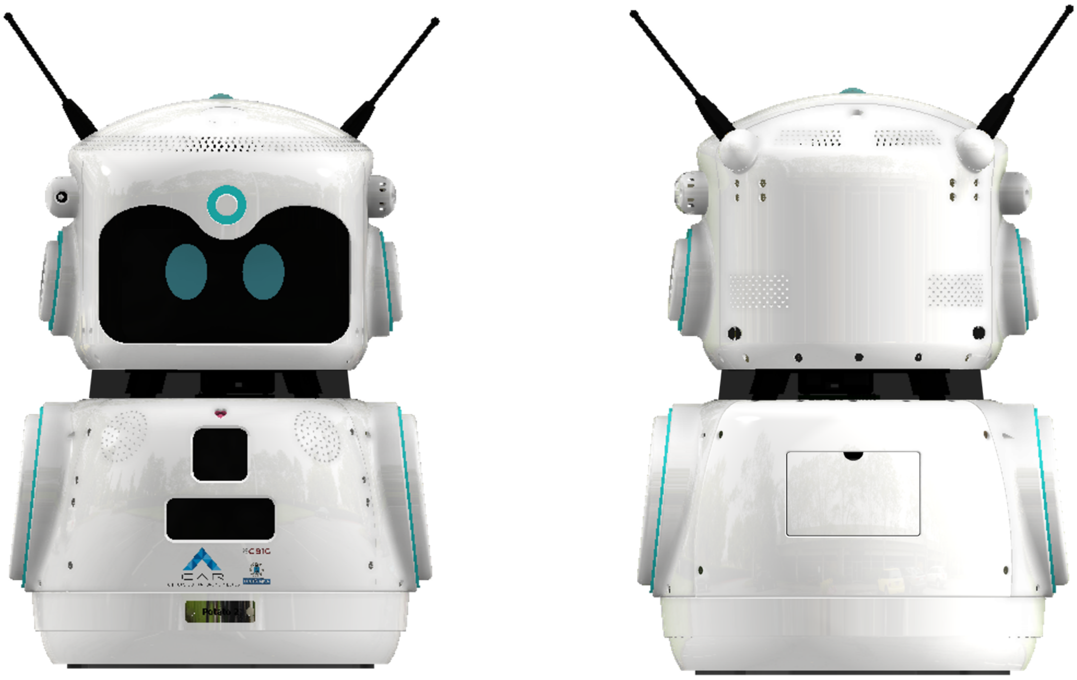
4.1.3.3. Safety Features

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.

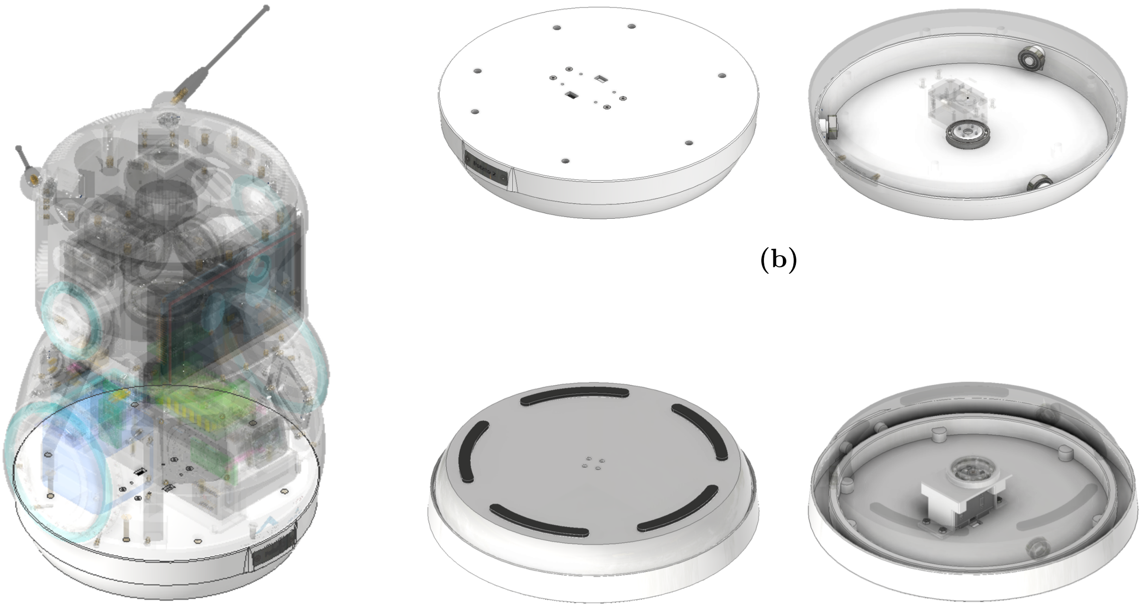


(a) (b)

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.



(b)

(a)

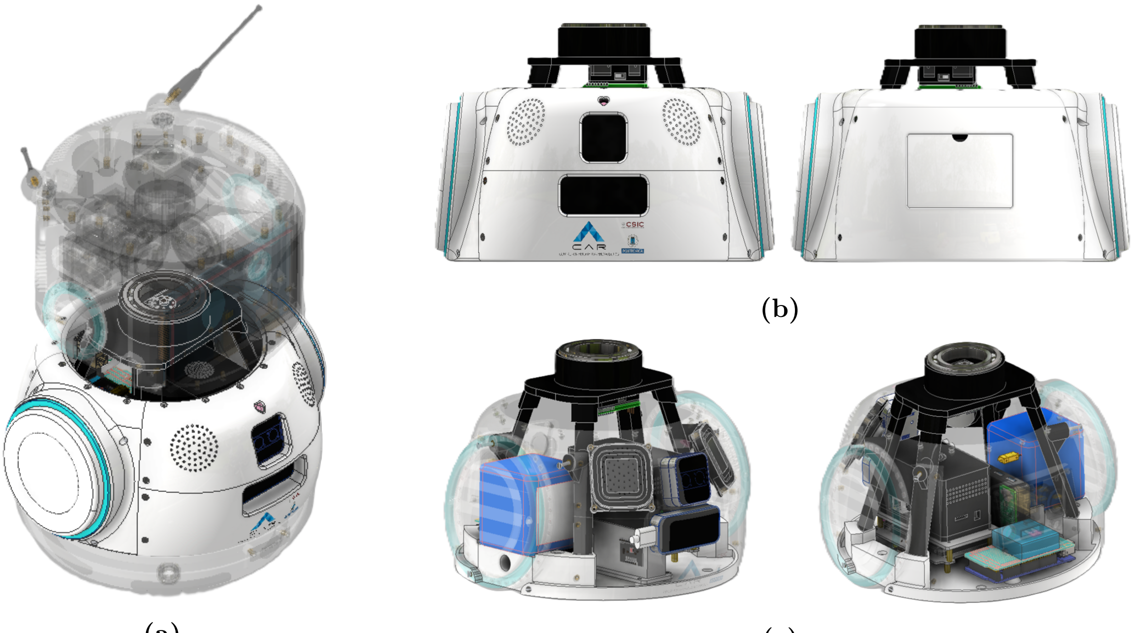
(c)

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.



(b)

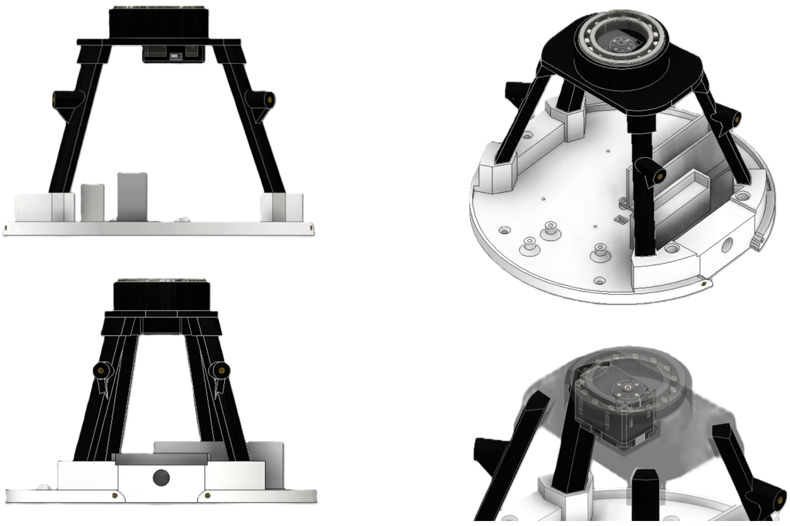
(a)

(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 **±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.

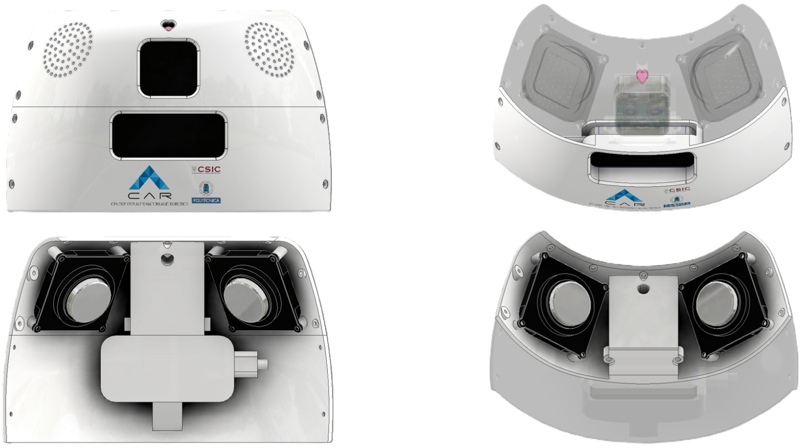


(a) (b)

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.

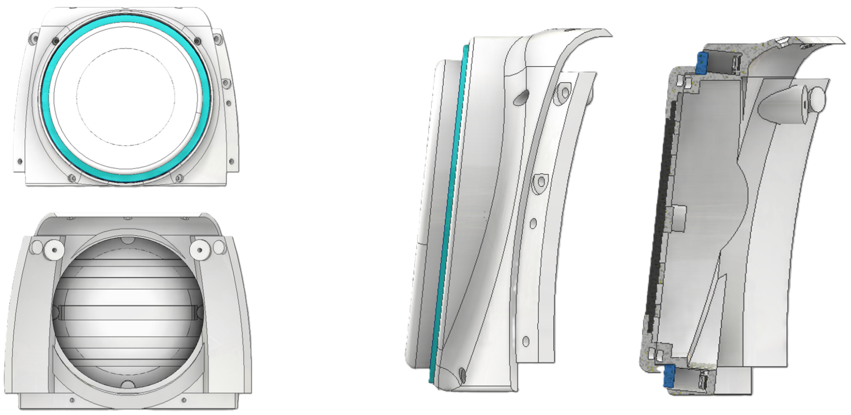
(a) (b)

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.

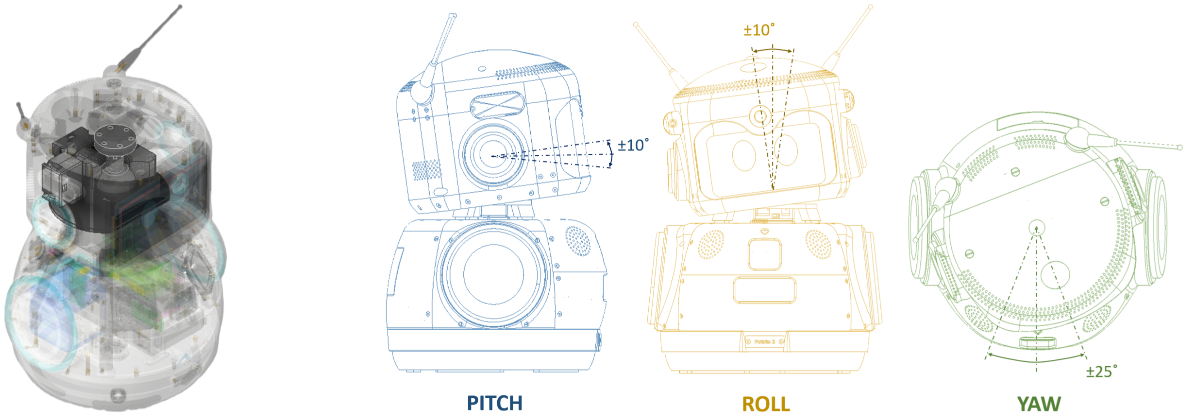


(a) **(b)**

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.

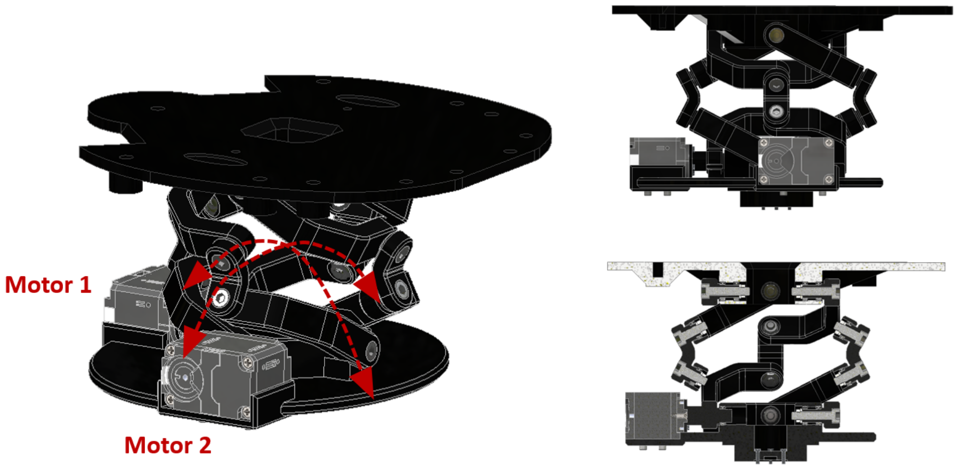
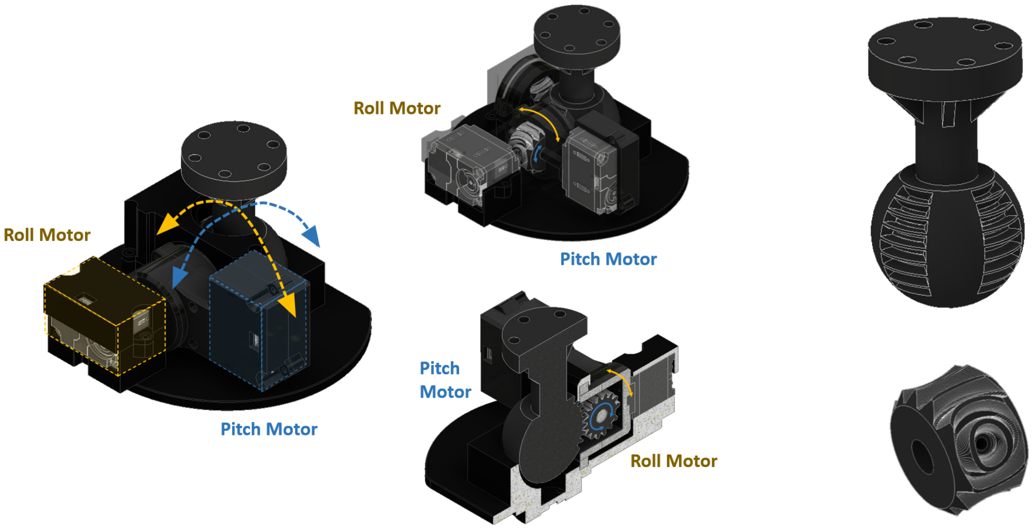


Figure 4.11. Actuation and details of the 2-DOF SPM.

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.



(a) (b)

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.

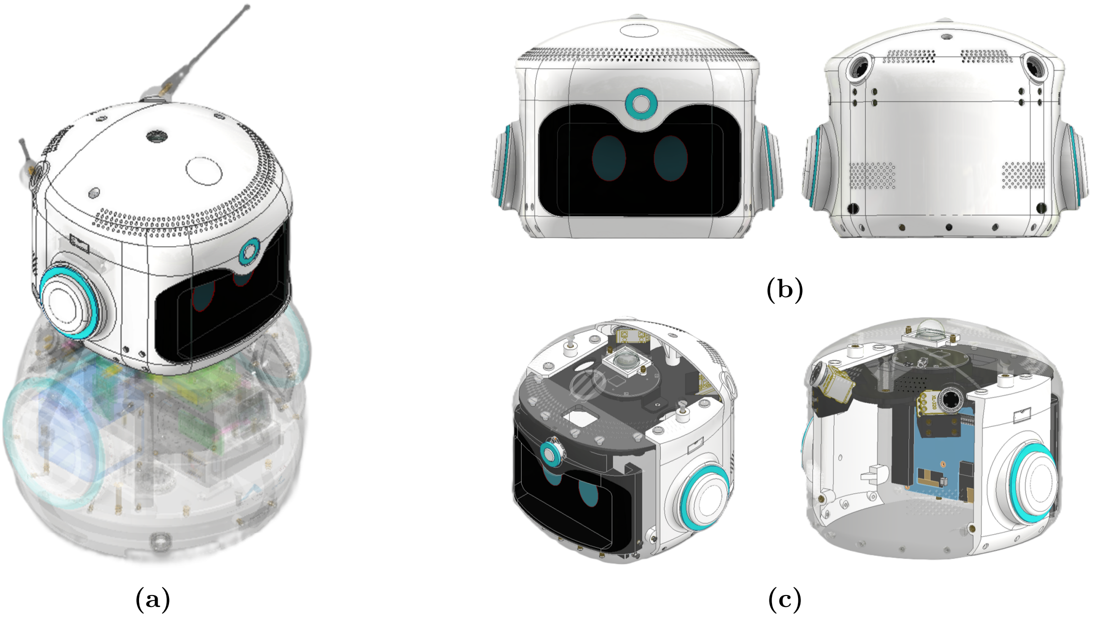

(a) (b) (c)

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.

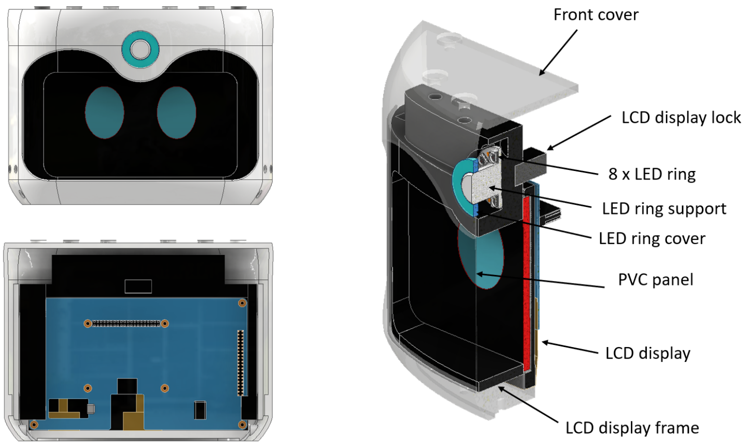

(a) (b)

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.



(a) **(b)**

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.

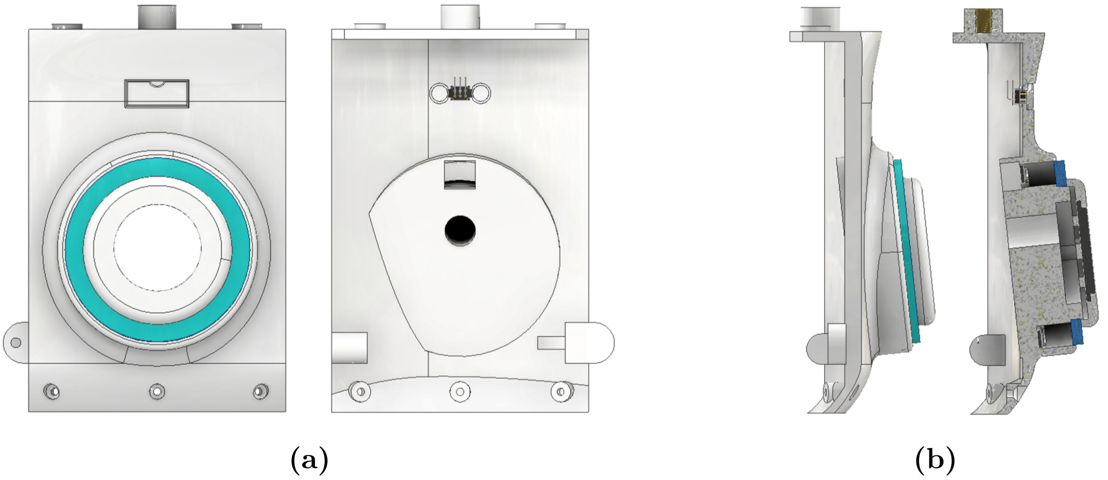


Figure 4.16. Details of the head lateral panels: (a) Front and back views, (b) Side view and cut view.

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.

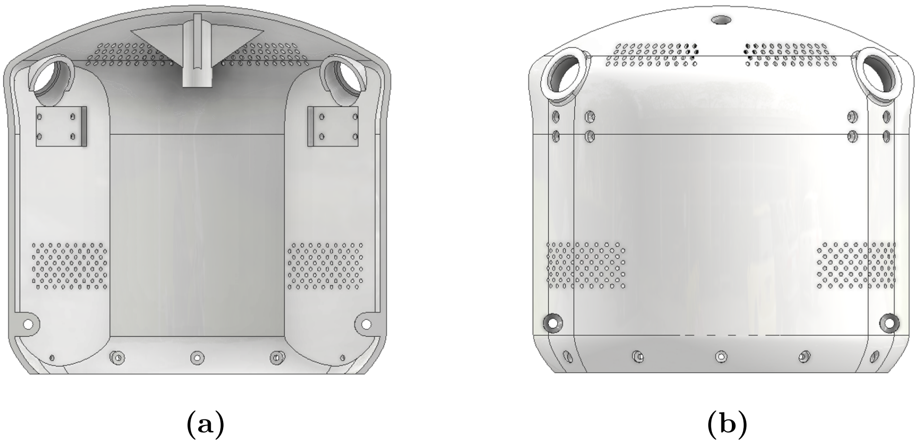
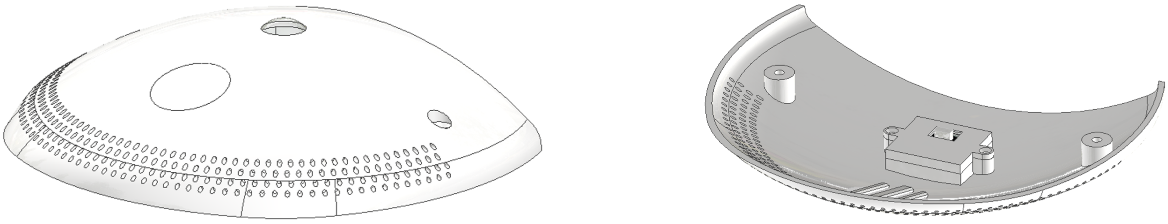


Figure 4.17. Details of the head back panel: (a) Front view, (b) Back view.

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.

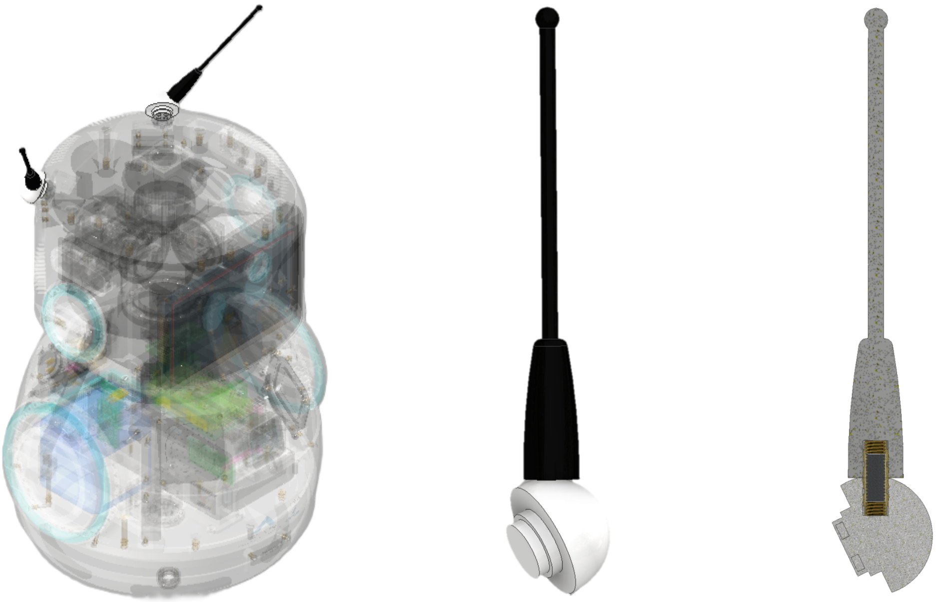


(a) (b)

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.

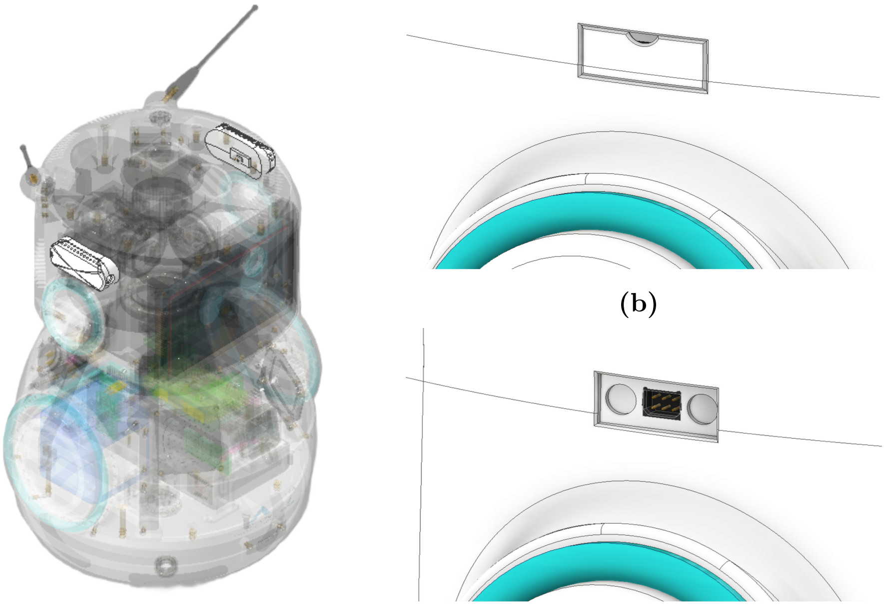


(a) (b) (c)

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)

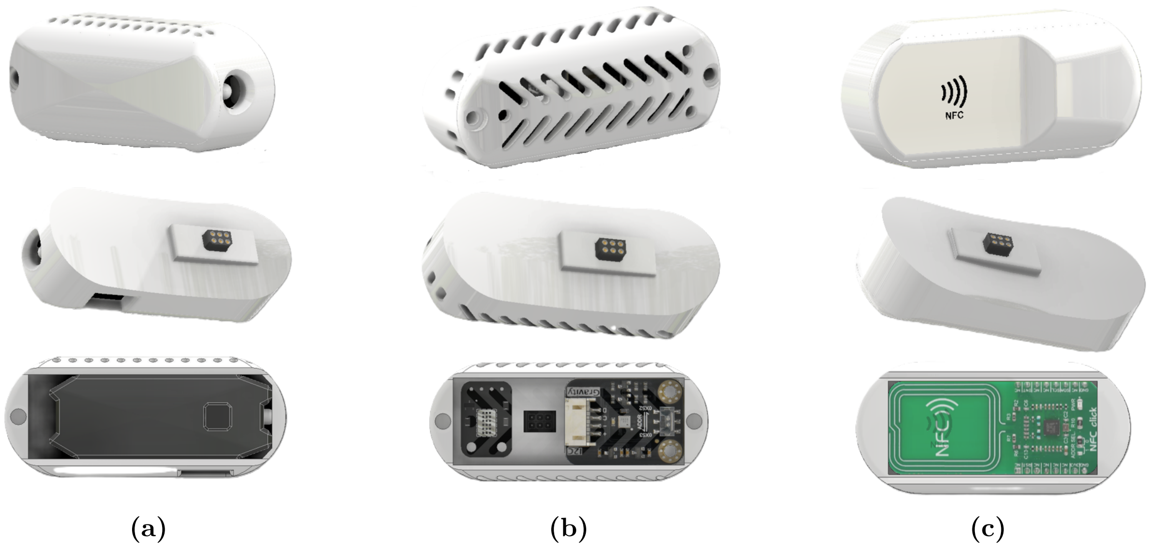
(c)

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.

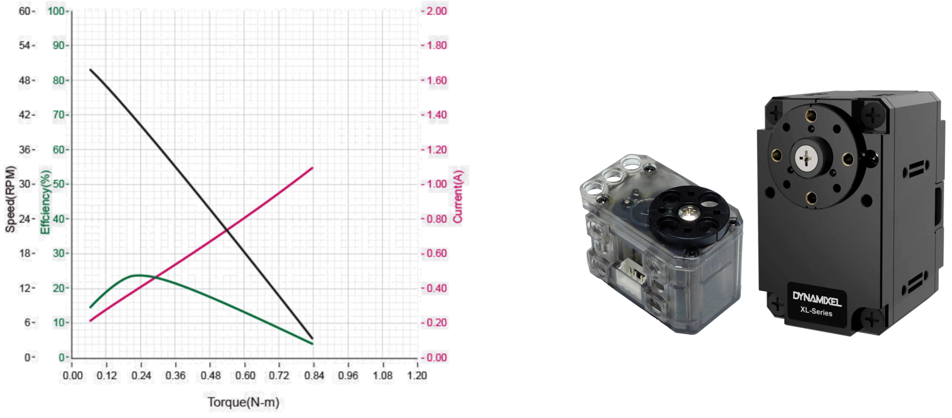
4.3.1. Actuators and Output Systems

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.

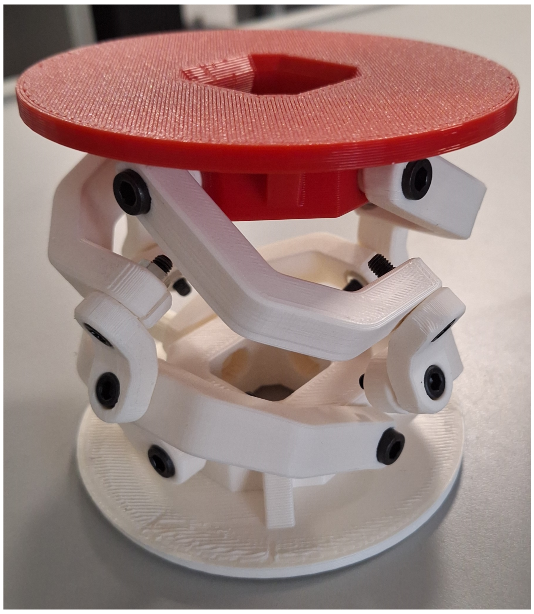


Figure 4.23. Testing initial neck mechanism prototype.

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)**

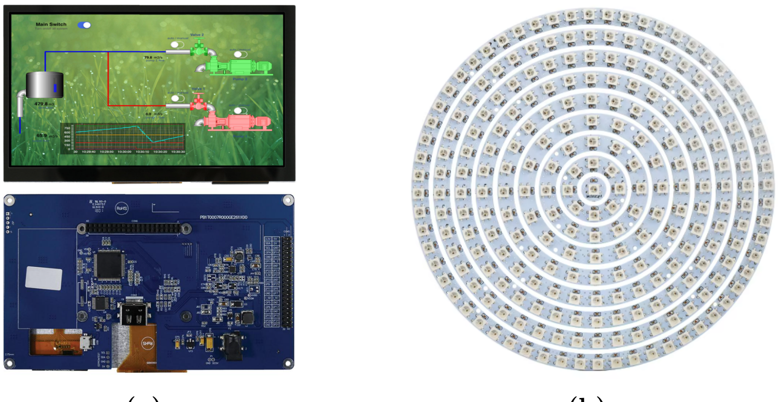
Figure 4.24. Audio subsystem: (a) Speakers [94], (b) Audio amplifier [95].

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.

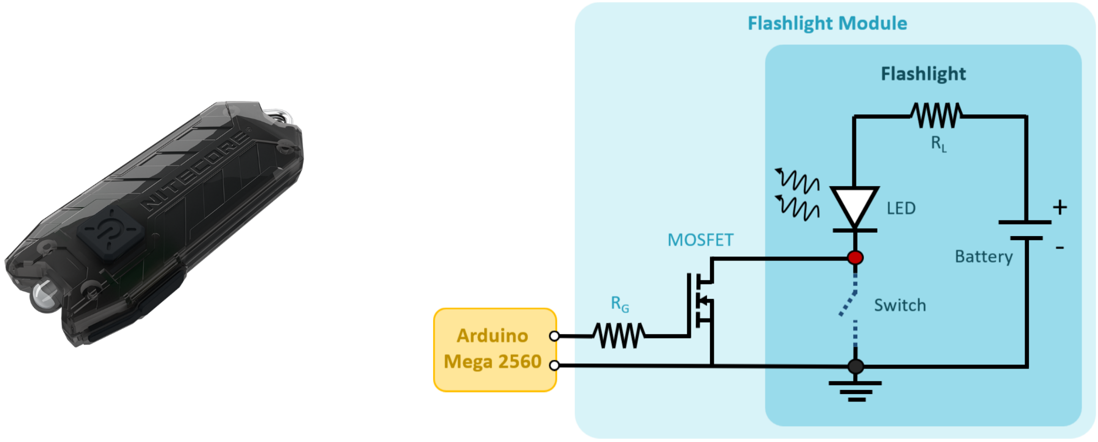


(a) (b)

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.

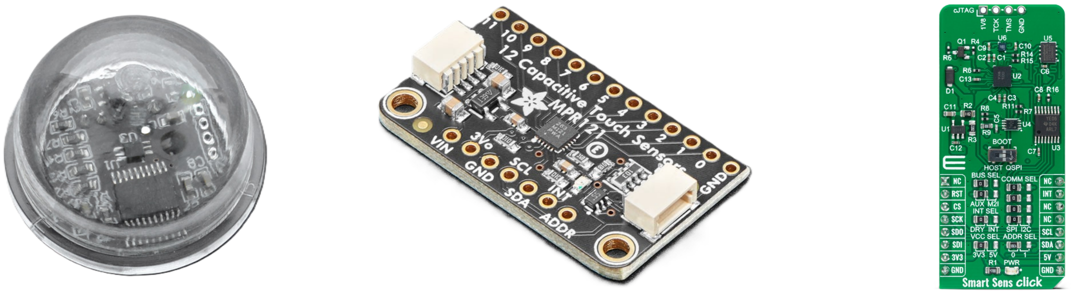
4.3.2. Sensors and Data Acquisition

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.

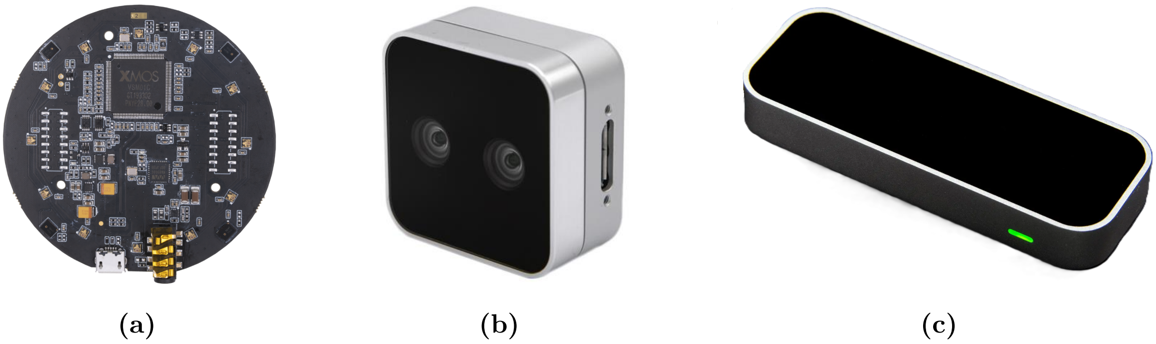

(a) (b) (c)

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.

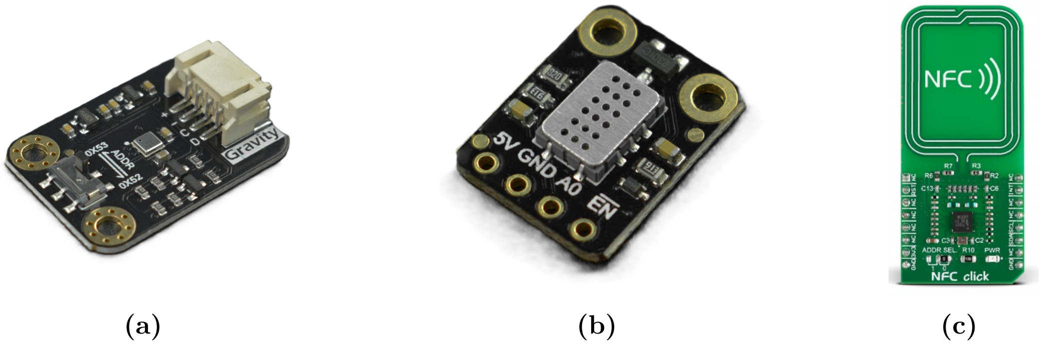


Figure 4.29. Environmental sensors: (a) Gravity ENS160 Air Quality [104], (b) Fermion MEMS Gas Sensor MiCS-5524 [105], (c) NFC Click module [106].

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.

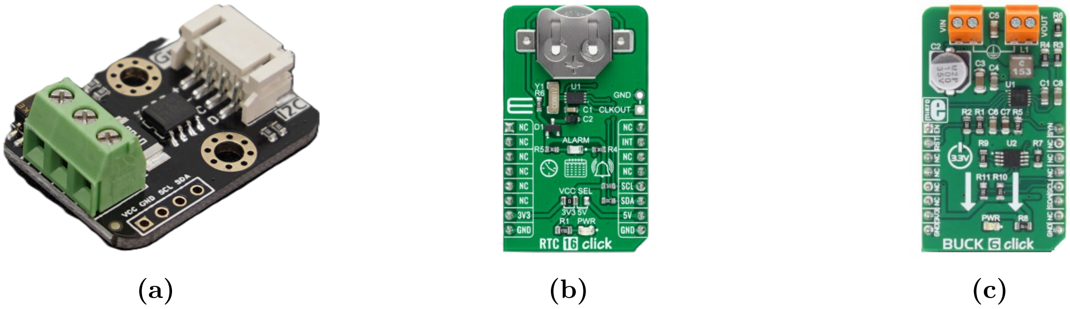

(a) (b) (c)

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.

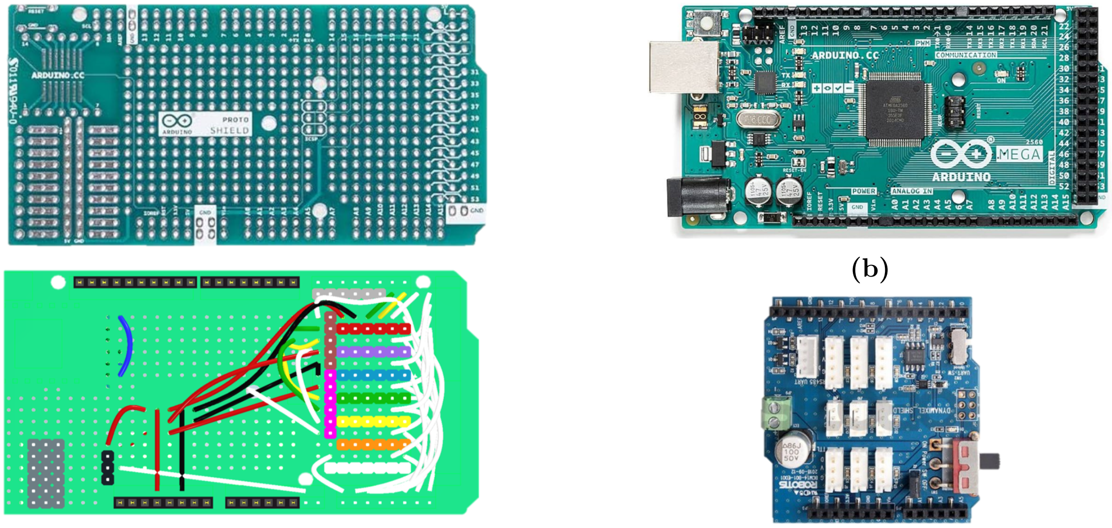
4.3.3. Control Systems

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

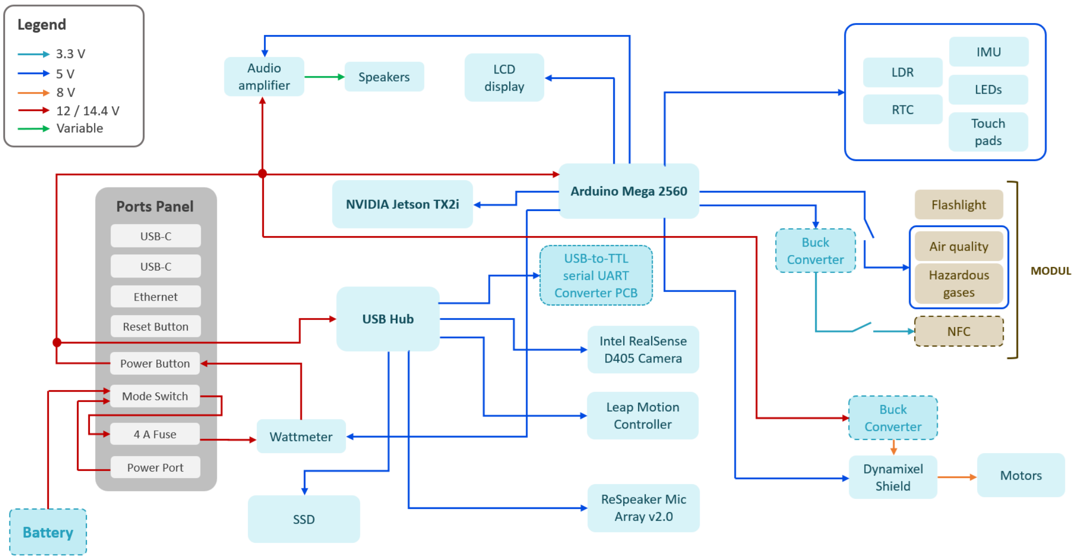


Figure 4.34. Overall designed power supply scheme.

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.

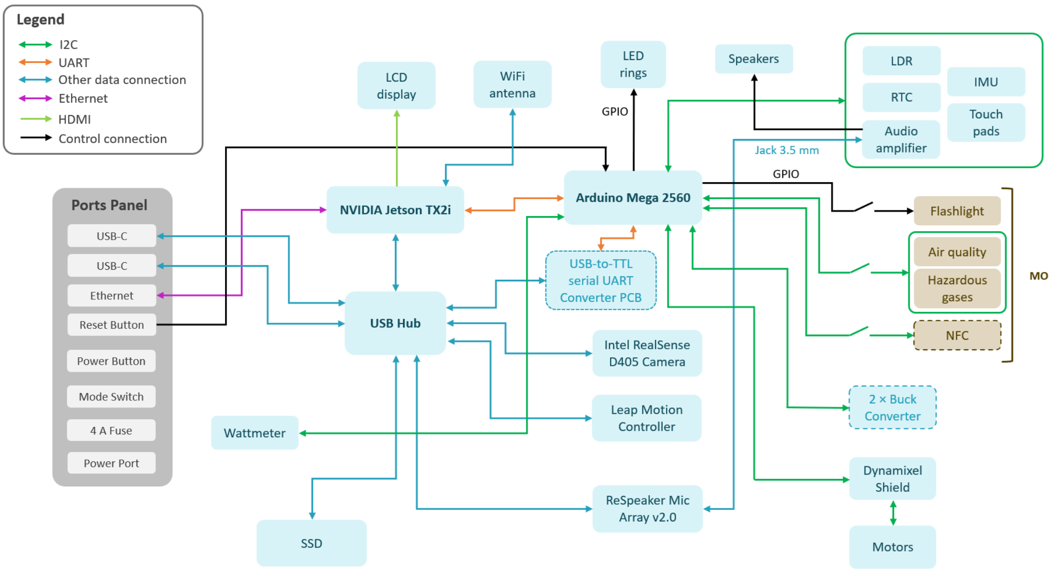


Figure 4.35. Overall designed communications scheme.

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

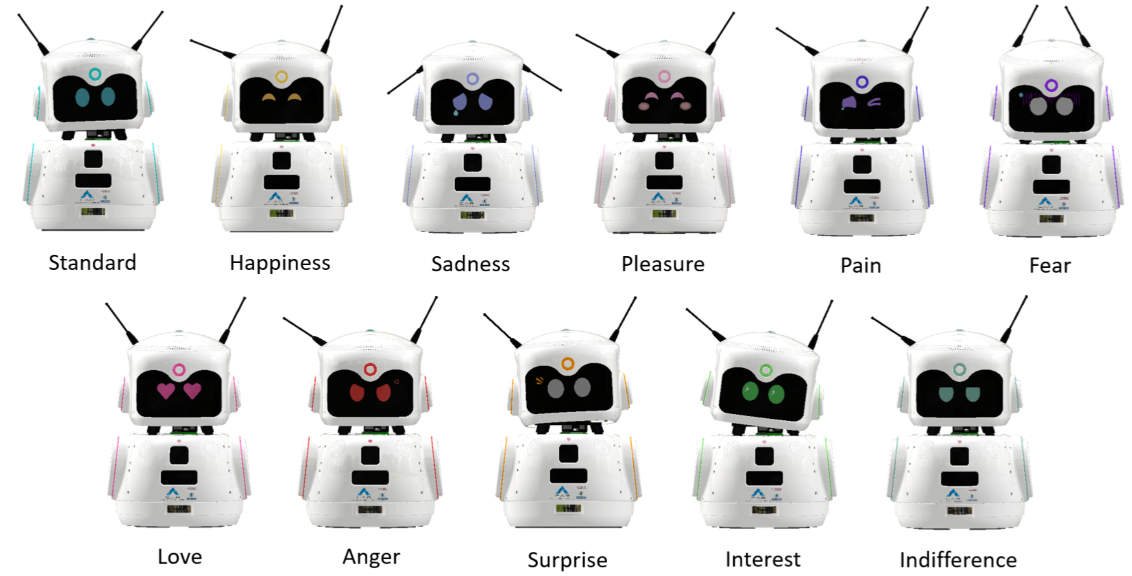


Figure 4.36. Set of designed robot emotions.

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.

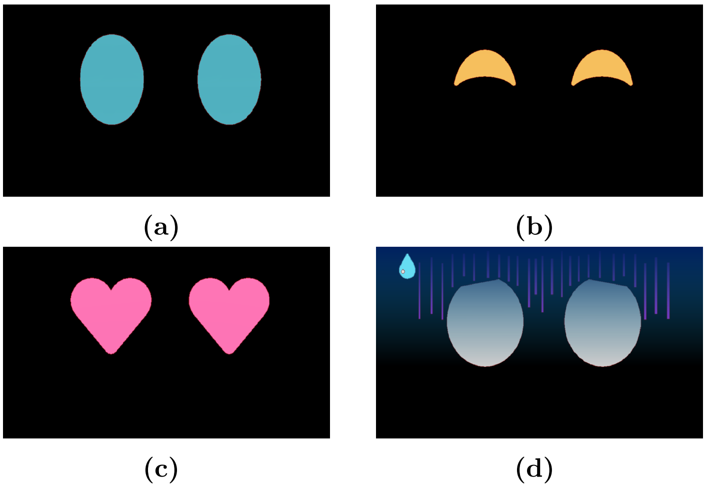

(a) (b) (c) (d)

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

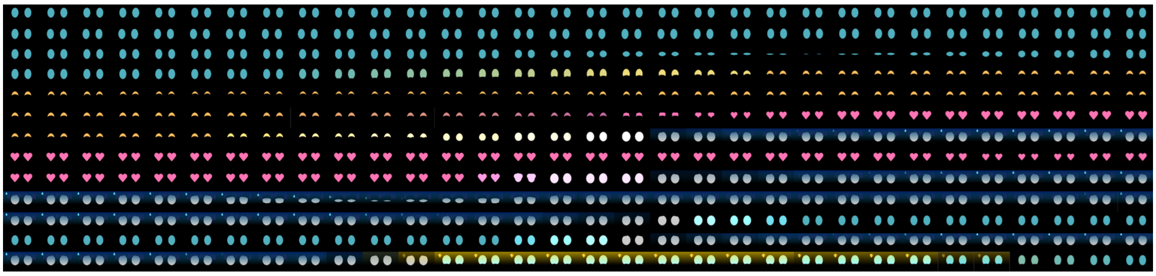


Figure 4.38. 13×32 spritesheet including 13 animations corresponding to four emotions and their corresponding transitions and some demo extra animations.

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.