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TRABAJO FIN DE MASTER

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

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Daniel Sotelo Aguirre

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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**, with the exception of some elements due to time constraints. This prototype was then submitted to several tests for validation purposes of its core functionalities.

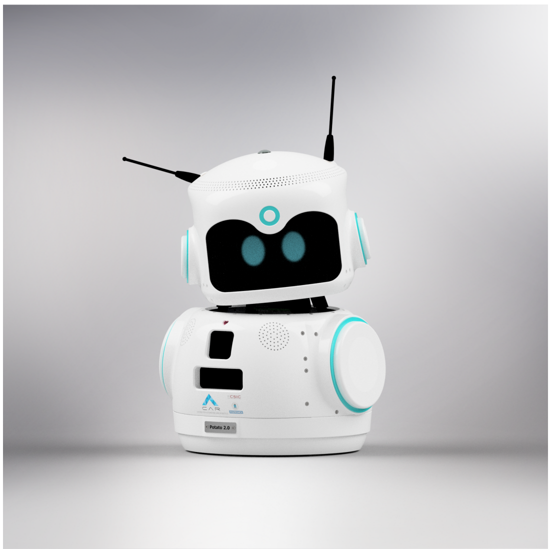

Figure R1. Personal assistance robot prototype render.

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 robot.

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, incluida 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. 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 la Universidad Politécnica de Madrid, 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 se 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**, a falta de la integración de algunos elementos por cuestiones de tiempo. Este prototipo se sometió a diversas pruebas para validar sus funcionalidades principales.

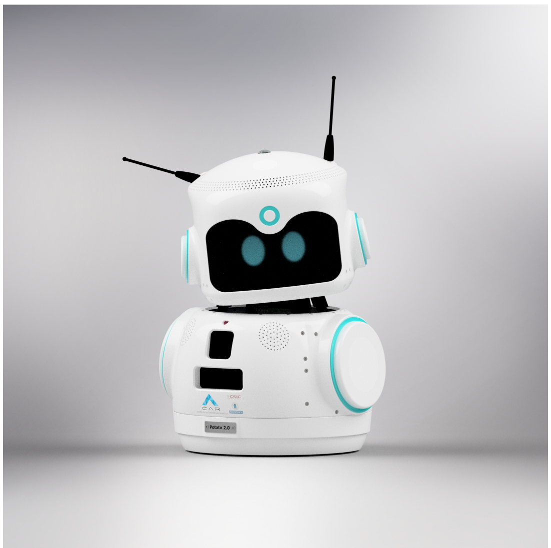

Figure R1. Render del prototipo de robot de asistencia personal.

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.

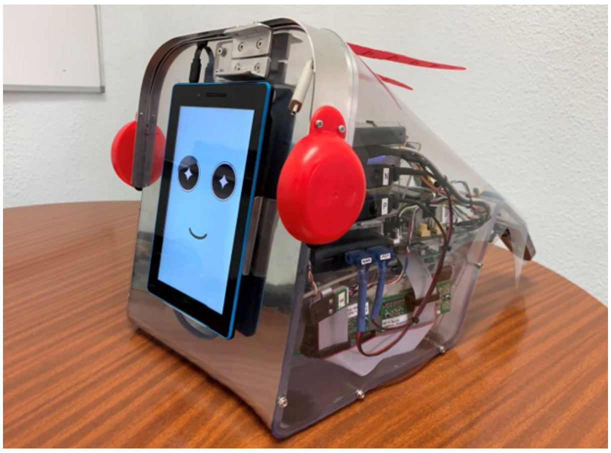

Figure 1.1. Potato personal assistance robot [3].

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].

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[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.

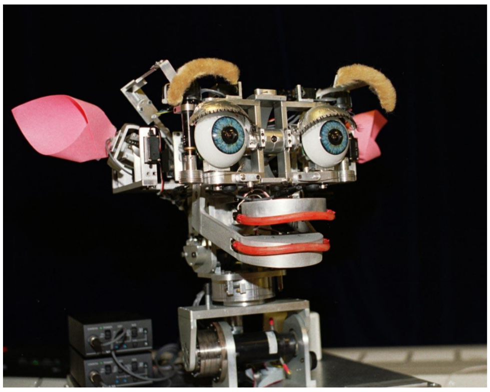


Figure 2.1. Kismet robot [5].

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 15th 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

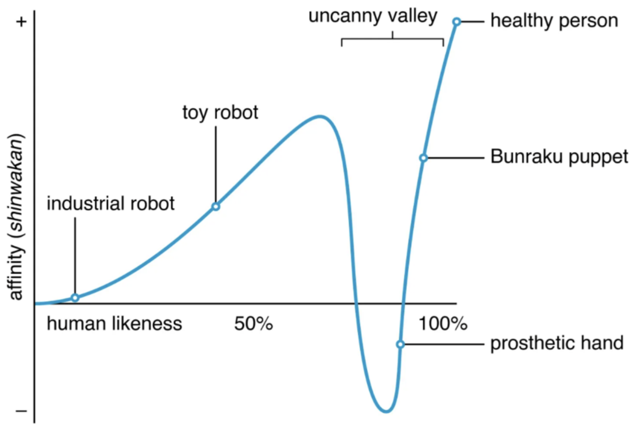


Figure 2.2. "Uncanny Valley" curve [28].

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.

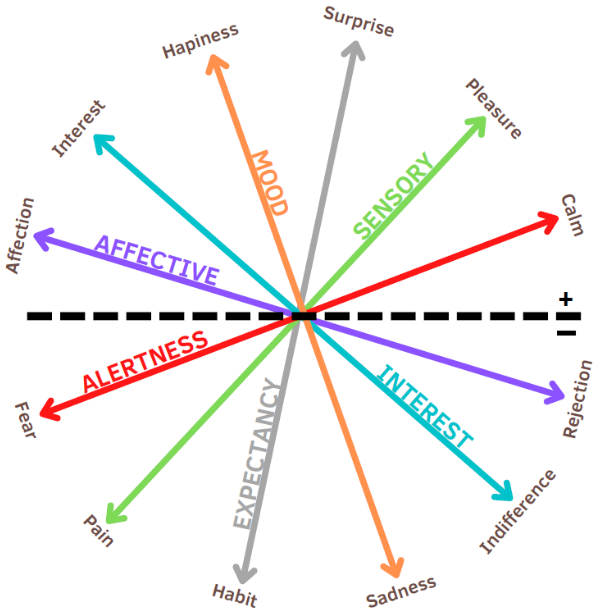


Figure 2.4. Representation of the emotions for the dimensional emotional model of Potato, proposed based on Plutchik's wheel of emotions [3][37].

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.

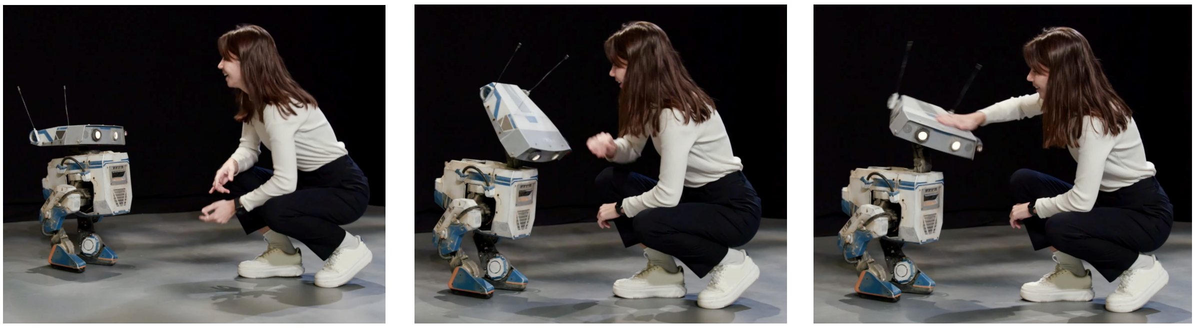


Figure 2.5. Disney Research bipedal robotic character interacting with a woman [44].

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.

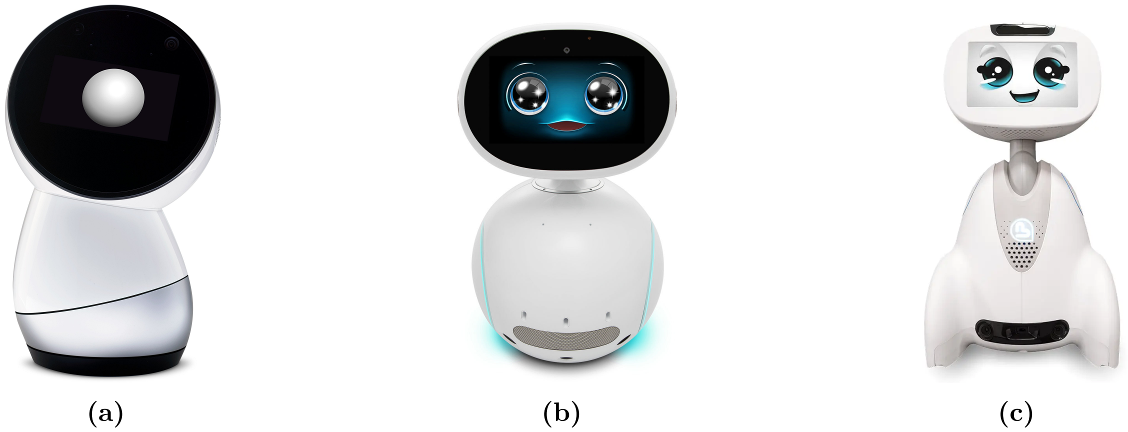

(a) (b) (c)

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.

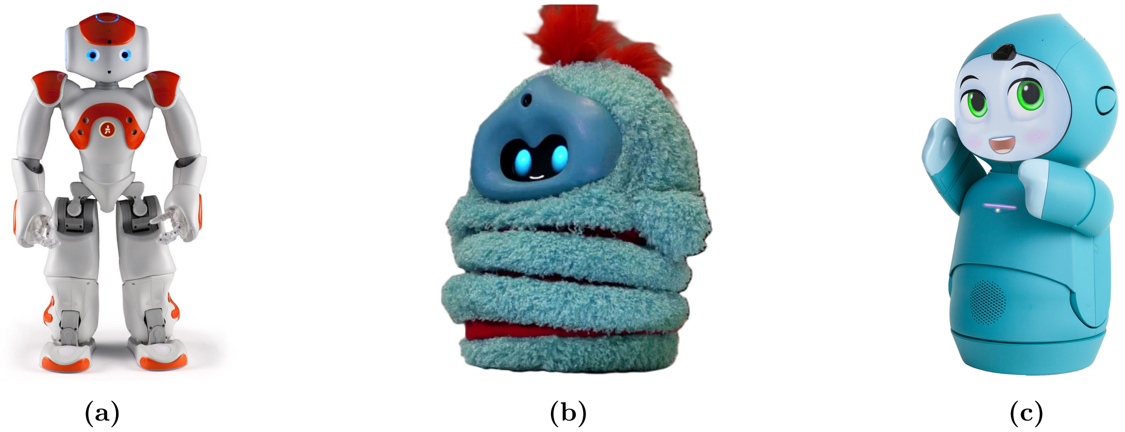
2.3.2. Education and Child Development

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].

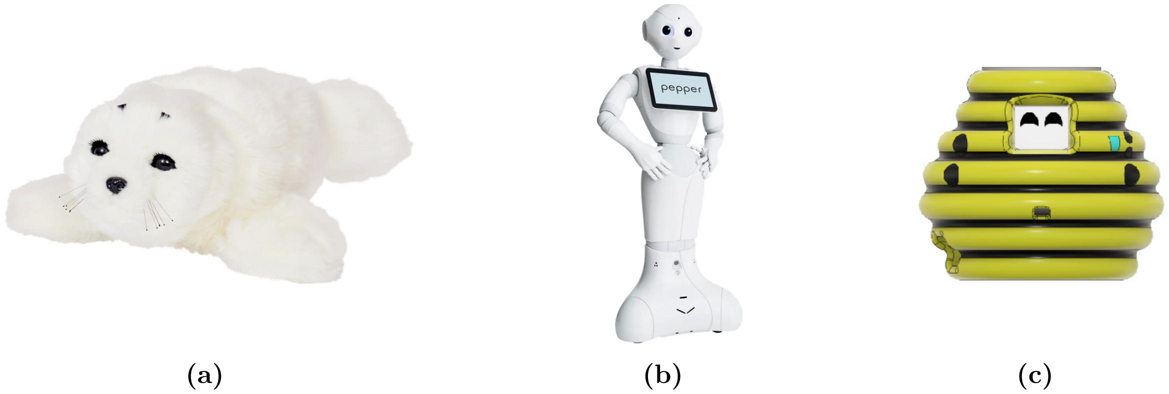
2.3.3. Healthcare and Elderly Care

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.



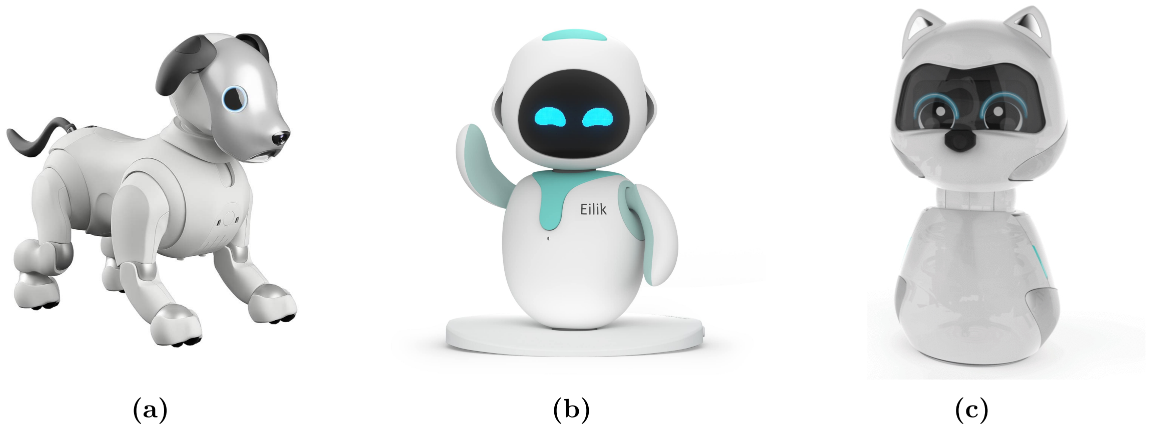
(a) **(b)** **(c)**

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.

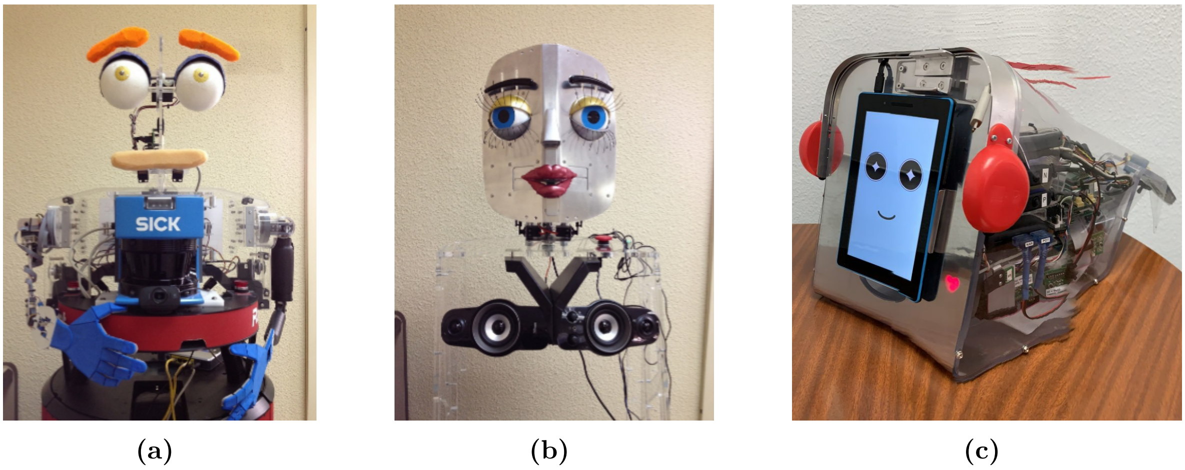


(a) **(b)** **(c)**

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

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[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.

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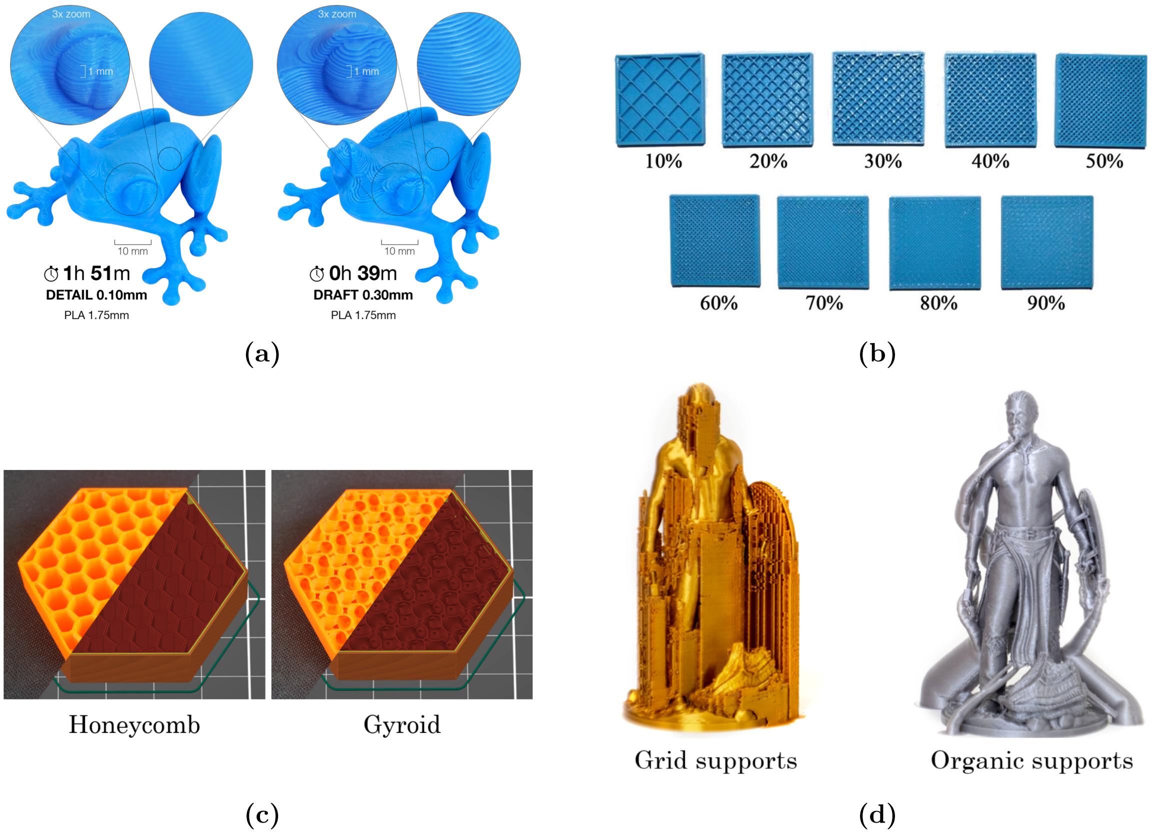
[2] Language that directs CNC machines and 3D printers on movements and actions.



(a) **(b)**

Honeycomb Gyroid Grid supports Organic supports

(c) **(d)**

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.

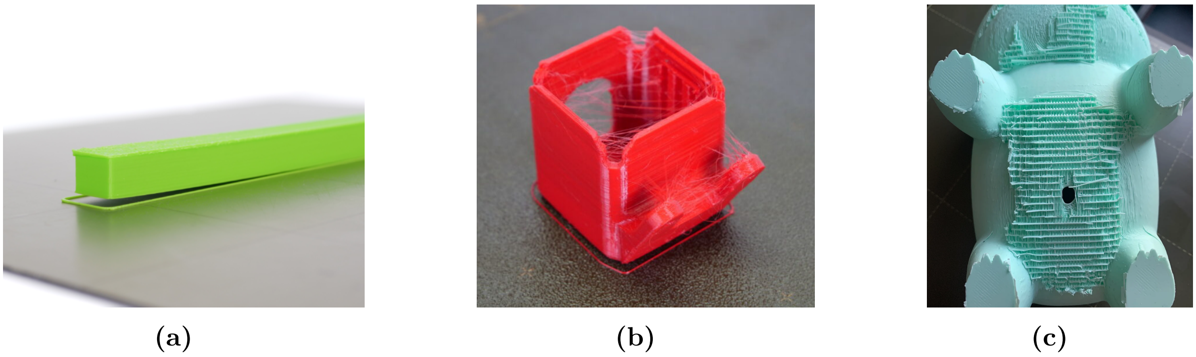

(a) (b) (c)

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.

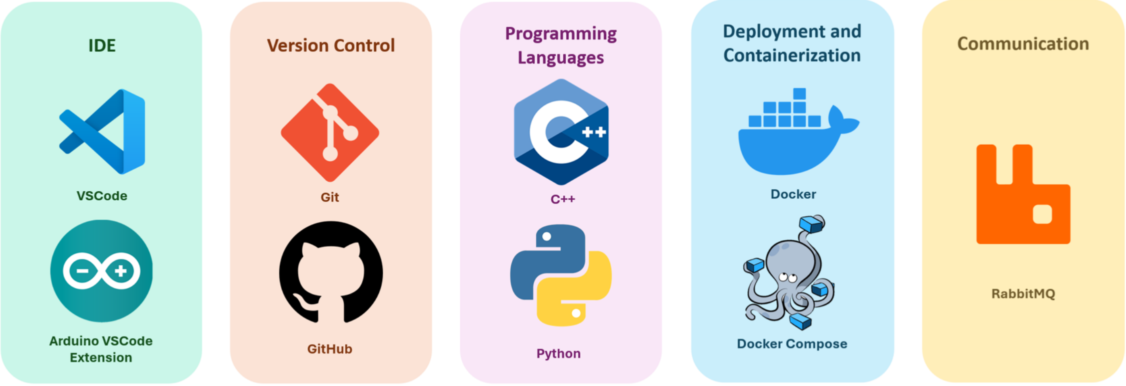


Figure 3.5. Summary of software development and deployment tools used in the project.

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.

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[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.