POLITECNICO
MILANO 1863

SCUOLA DI INGEGNERIA INDUSTRIALE
E DELL'INFORMAZIONE

Odile: an Expressive Robotic Agent for Emotional Exchange and Information Sharing

Tesi di Laurea Magistrale in
Computer Science and Engineering
Ingegneria Informatica

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Academic Year: 2022-23

Abstract

Interaction is a process in which two or more individuals exchange information bi-directionally. Focusing on the social context, this phenomenon is composed of many variables that depend on both the surrounding environment and the characteristics of the concerned individuals. These variables can be combined in different ways and can generate opposite results.

Very often, interaction in a social context is also characterized by an emotional connection between individuals. They may use words and body language to communicate their mood and emotions at a particular time, not necessarily in the present. This phenomenon has been studied in various fields, such as business, politics, and the arts. Of particular interest to us is the field of art and theatre because of the need to establish an emotional relationship between the performer and the audience.

Actors use several methods to express emotions. The school of theatre focuses on the study of the body movement, characterized by rhythm, amplitude, and speed of the limbs as well as combinations thereof.

In modern times, this concept has also been linked to the film industry, particularly animation. Animating an inanimate object requires a thorough study of all the movements it can make, dependent on the structural characteristics of the body.

With the advancement of technology, the concept of animation has also been extended to more or less complex robotic structures, creating so-called animated robots.

This thesis aims to realize a robot capable of communicating information and emotions in an interaction with an external human agent. We have introduced constraints to the study, such as the requirement for non-verbal communication and a robot's shape as far as possible from human geometry. In this way, we focused on the movements and articulation of the structure.

Odile is the robot designed and implemented for this study. It is a mobile robot with two similarly structured extensions, one more articulated than the other. Overall, the structure has thirteen degrees of freedom, which makes the robot complex and capable of performing a wide range of movements.

We tested Odile's capabilities in a game interaction where the exchange of information is necessary for the user to win. The proposed set-up consists of a maze with buttons scattered around the room; some are correct. A countdown tells the player how much time is left to complete the game. To test both the pure information exchange capacity and the expressive capacity of the robot, we proposed two different experiences. In both cases, only the robot knows which of the buttons are the correct ones. A successful experiment is one in which the user shows trust in and understanding of what the robot is communicating.

Odile is not to be considered as autonomous. We created a control module that allows the robot's movements to be managed remotely in real time.

The results were satisfying, proving that the efficient exchange of information through pure movement is possible even without verbal interaction or humanoid structures.

Future developments concern the possibility of new movement configurations and more complex and cleaner control.

Keywords: interaction, emotionality, robot, movement

Abstract in lingua italiana

L'interazione è un processo in cui due o più individui si scambiano informazioni in modo bidirezionale. Concentrandosi sul contesto sociale, questo fenomeno è composto da molte variabili che dipendono sia dall'ambiente circostante sia dalle caratteristiche degli individui interessati. Queste variabili possono essere combinate in modi diversi e possono generare risultati opposti. Molto spesso l'interazione in un contesto sociale è caratterizzata anche da una connessione emotiva tra gli individui. Questi possono usare le parole e il linguaggio del corpo per comunicare il proprio stato d'animo e le proprie emozioni in un momento particolare, non necessariamente nel presente.
Questo fenomeno è stato studiato in vari campi, come economia, politica e arte. Di particolare interesse per noi è il campo dell'arte e del teatro per la necessità di stabilire un rapporto emotivo tra l'attore e il pubblico. Gli attori utilizzano diversi metodi per esprimere le emozioni. La scuola di teatro si concentra sullo studio del movimento del corpo, caratterizzato dal ritmo, dall'ampiezza e dalla velocità dei gesti e dalle loro combinazioni. Nei tempi moderni, questo concetto è stato collegato anche all'industria cinematografica, in particolare all'animazione. Animare un oggetto inanimato richiede uno studio approfondito di tutti i movimenti che può compiere, in funzione delle caratteristiche strutturali del corpo. Con l'avanzamento della tecnologia, il concetto di animazione si è esteso anche a strutture robotiche più o meno complesse, creando i cosiddetti robot animati.
Questa tesi si propone di realizzare un robot in grado di comunicare informazioni ed emozioni in un'interazione con un agente umano esterno. Abbiamo introdotto alcuni vincoli nello studio, come il requisito della comunicazione non verbale e la forma del robot il più lontano possibile dalla geometria umana. In questo modo ci siamo concentrati sui movimenti e sull'articolazione della struttura.
Odile è il robot progettato per questo studio e oggetto di questa discussione. Si tratta di un robot mobile con due estensioni strutturate in modo simile, una più articolata dell'altra. La struttura ha tredici gradi di libertà, il che rende il robot complesso e capace di eseguire un'ampia gamma di movimenti.
Abbiamo testato le capacità di Odile inserendo l'interazione all'interno di un gioco e rendendo lo scambio di informazioni necessario all'utente per vincere. L'allestimento proposto

è costituito da un labirinto con bottoni sparsi per la stanza; di cui solo alcuni corretti. Un conto alla rovescia dice al giocatore quanto tempo rimane per completare il gioco. Per testare sia la pura capacità di scambio di informazioni che la capacità espressiva del robot, abbiamo proposto due diverse esperienze. In entrambi i casi, solo il robot sa quali pulsanti sono quelli corretti. Un esperimento riuscito è quello in cui l'utente mostra fiducia e comprensione di ciò che il robot sta comunicando.
Il robot in questione non è da considerarsi autonomo. Abbiamo realizzato un modulo di controllo che permette di gestire i movimenti del robot da remoto e in tempo reale.
I risultati sono stati soddisfacenti, dimostrando che lo scambio efficiente di informazioni attraverso il puro movimento è possibile anche senza interazione verbale o strutture umanoidi.
Gli sviluppi futuri riguardano la possibilità di nuove configurazioni di movimento e di controllo più complessi e puliti.
Parole chiave: interazione, emotività, robot, movimento

Contents

1 | Introduction

1.1. Aim of the project

Nowadays, being able to interact proficiently with a robot is no longer a science-fiction experience often described in novels or films. Recent technological developments have shown how a robot can effectively engage in a conversation, entertain, and help the people around it.

The field of social robotics is concerned with researching new methods to bring these devices as close as possible to humans. This field has been the subject of exponential attention in recent years. Numerous leading firms, organizations, and institutes have been conducting studies with the shared ambition of bringing a lifeless object to life.

Keeping this objective in mind, we wanted to explore one of the relevant elements that comprise social interaction between people, such as movement. Expression through gesture is used in many social contexts. It facilitates the speaker to stress the speech, letting the emotions experienced at that moment be seen and revealing an individual's character.

This thesis aims to create a robot capable of representing different states of mind through the movement of its joints.

We approached the study of gestures using theory from plays, dance and ballet, cinema, and animation. We took the main and common concepts between all these arts and used them to define forms and mechanisms that could be sensible and usable in different configurations. Our idea is to bring the robot to be as expressive as possible, capable of representing various emotions within an interaction with an individual.

The robot created was named Odile, about the opera *Swan Lake* precisely because it was inspired by the gestures typical of dance and ballet.

The main objective is to get in tune with the person with whom one is interacting so that they can understand both the message that the robot wants to communicate and the emotional state with which it is conveying it. The entire interaction must take place exclusively through gestures. We did not want to use any other mechanism to support the conversation, such as visual or sound effects.

Another constraint we set ourselves concerns the shape of the robot. Much research has

been done on the expressiveness of humanoid structures. It has been seen how to implement mechanisms that can replicate the movement of human joints.
This project aimed to uncover the artistic possibilities of an unfamiliar shape that cannot be linked to human form. The aim is to study the principal elements of non-verbal communication and apply them to human-robot interaction in an innovative way that does not use bodies with intuitive human shapes.
This study could be used to research different movement configurations capable of handling interaction with multiple people. In addition, this work offers a basis for further study of the feedback needed for a person to feel involved during both a physical and emotional exchange.
The project was executed within the *Physical Metaverse* context, which seeks to generate a real-world tangible experience. For this reason, we did not make Odile autonomous but fully controlled. In doing so, we emphasized the deformability of the structure, which can change configuration and represent different emotional states.

1.2. Thesis structure

This dissertation consists of 5 chapters.
In order:

- Chapter 2 - **Status and Background**
  These pages contain all the relevant information which was taken into account during the development of this thesis.
- Chapter 3 - **Theoretical Description**
  This chapter describes the development process, including the reasons for the choices made.
- Chapter 4 - **Project Implementation**
  This section contains specifications for the physical and software implementations of the robot structure.
- Chapter 5 - **Experiments**
  This chapter includes all the relevant information about the experimental procedure, the testing of the robot, and the presentation and analysis of the results.
- Chapter 6 - **Conclusions and future developments**
  In this last part of the document, some final reflections on the project are given, with a view to possible directions for the future.

2 | Status and Background

Studying the interaction between two people is part of the science of body language, called kinesics.

Kinesics [63] is a fundamental aspect of communication and is therefore considered in various fields: education, marketing and advertising, law, and politics. The study of interaction is also used in performing and visual arts: understanding how two people may interact in different situations, in which body movements and facial micro-expressions emphasize a particular emotion by distinguishing it from another, allows the performance to be as truthful and engaging as possible. Suppose we apply this communicative study of representational arts to human-robot interaction (HRI). In this case, we can derive basic behaviors and movements that an automaton should show for an effective exchange of information between the two. To better understand the motivations behind the design choices, we present a general description and an overview of the research that has been carried out on expressive movement and the role of robots as communicative agents.

2.1. Interaction

During the development of this project, we focused on the study of the interaction between two individuals using theatre, dance, animated films, and exhibition art as reference points. In all of these fields, understanding how a body moves and interacts is fundamental to ensure that the intended emotion reaches the audience clearly and directly. We used the concepts learned to explore the range of minimum movements required for a robot to elicit a meaningful response from people. We then used the selected gestures to define the structure of the robot and the different articulations it could take.

2.1.1. Theatre

Interaction plays a fundamental role in the vast majority of theatrical performances. A performance consists entirely of dialogues that can be exchanged between actors or actors and the audience.

During the exchange of lines, the actor has to make a series of adaptations in the way

he expresses himself and moves so that the audience understands the exact nuance of the emotion the character is feeling at that moment in the story.
The study of movement-related personalities is fundamental, and it is possible to establish a correspondence between a specific emotion and a set of gestures and movements that characterize it.
K. Stanislavsky was one of the first theatre theorists to introduce a method of training actors in movement and interpretation [6]. Especially in the final version of his method, even before learning lines, actors must feel and perform actions convincingly and automatically so that they are as true to life as possible. According to this method, an action must be accentuated and convincing in the eyes of a spectator far away from the stage.
The diagram below [Figure 2.1] shows the two aspects of role performance. The left branch illustrates the notion of *experiencing the role* related to the request made to the actor to think and feel emotions similar to those of the character he has to play. The right branch illustrates the notion of *embodiment*. This concept refers to the actor's ability to "step into the boots" of the character and assume his characteristics. These two branches are connected by the common goal of achieving the highest *supertask*, which is the natural portrayal of the role.

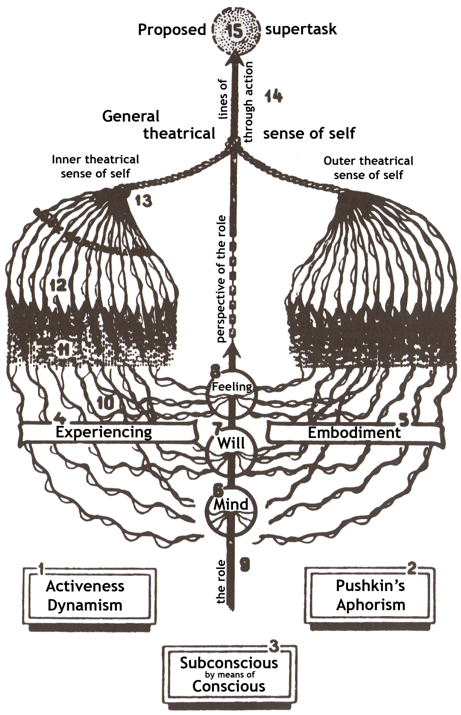


Figure 2.1: Stanislavsky's system for actors

Mimicry

Mime is a theatrical form that originated in ancient Greece and Rome and is defined as the representation of actions and stories using only gestures and facial expressions [60]. We studied this type of theatrical form to understand from where in the body a movement originates, what articulations are required to generate it, and how an intention can be recognized without words.

At the end of the 19th century and the beginning of the 20th century, there was a rediscovery of the body as central to the expressiveness of the actor. Several schools for the physical training of performers emerged in this period. The first to introduce a school focused solely on physical movement, the study of expressions and gestures, was Étienne Decroux [16]. After studying with Jacques Corpeau, he opened his school in the 1940s, thus creating the new art of mime.

Decroux moved away from the stereotypical conception of 19th-century mime and focused on using the torso as the main point of expression. He also used a non-descriptive approach to his subjects but searched for non-natural and plastic movements using inexpressive masks or semi-transparent veils. His research is aimed at finding a precise and essential gesture.

After establishing his new mime school, Decroux wrote "The Dramatic Corporal Mime". In this treatise, movements are defined both individually and in sequence. Any expressive movement can thus be broken down, described neatly, and reproduced on stage.

The most important actors of the French mime school were the pupils of Decroux. To name a few: Jacques Lecoq and Marcel Marceau.

Jacques Lecoq [18] was a French theatre actor and mime. Given his interest in sports, especially gymnastics, he began to study the geometry of movement and how to manage space around the body. In the 1940s, he taught the art of motion in the theatre company Comédiens de Grenoble, where he began to learn about masks as a form of theatre. At the end of the 1940s, he went to Italy for a period where he discovered and studied Commedia dell'Arte and acted with Dario Fo.

He later returned to France and opened his School of Mime and Theatre (today known as École Internationale de théâtre Jacques Lecoq). Lecoq introduced new teaching methods into the physical theatre. Physical theatre [67] is the name given to a type of theatrical performance that focuses on movement and gesture.

His teaching method was based on leaving it up to the students to find ways of performing the script that suited them best while focusing on and pointing out only the negative aspects of performance so that students were encouraged to find new ways to improve using creativity. In his lessons, he introduced the *neutral mask* [Figure 2.2]. It is a symmetrical mask with thin eyebrows and a mouth with a generic expression that can be matched to any action. Using this mask, students are forced to make open, precise movements and interact as much as possible with the environment. Once a certain level of naturalness has been achieved with the neutral one, the course moves on to other types of masks, more specific to the character being played.

Figure 2.2: Neutral mask used by Jacques Lecoq during his lectures

Between the late 1960s and the late 1980s, Jacques Lecoq taught at the Ecole Nationale Supérieure des Beaux-Arts, where he developed a study program on the architecture of the human body, movement, and the 'dynamics of mime' and created a new department within the school called LEM (Laboratoire d'étude du Mouvement). Lecoq traveled the world to spread his idea of movement and mime through his performance lecture entitled 'Tout Bouge' (Everything Moves), in which his entire theory was summarised.
Another Decroux's student was Marcel Marceau [1]. Even before meeting Decroux, Marceau developed physical and mimicry skills during the war. In August 1944, after the liberation of Paris, he gave his first public performance.
Marceau returned to Paris after the war. There he met Étienne Decroux and studied acting and mime. His first performances were very successful, and in 1947 he created Bip the Clown, who would remain his most famous character.
Marcel took the mime techniques used by Charlie Chaplin in his films and used them as a reference. He concentrated mainly on satire, looking for movements and expressions that could capture the spectator, generating emotions of laughter and curiosity. Iconic was his statement calling, 'the art of miming' as *the art of silence*.
Modern mime art is characterized by several schools, not only the French school. One example is the British-born Lindsay Kemp [30] .
He studied theatre and dance techniques, learned the Laban technique, and worked with Marcel Marceau to improve gestures. Marceau helped Kemp to refine the flexibility of his

hands. He also taught him silence and stillness.
Kemp takes inspiration from Eastern theatre, in particular Kabuki theatre and Trance. He was the first to introduce these styles into Western theatre.
Kabuki is defined as 'popular theatre' originating in Kyoto in which performances consisted of pantomime dances, initially performed by women only, who were later joined and even replaced by male dancers.
Trance was of fundamental importance to Lindsay as a theatre of total transformation. On stage, the ego disappears, and the character takes over completely. It is as if an experience of embodiment has been brought to the theatrical stage.
Kemp introduced the ritual of make-up as a passage to the theatrical performance, which allowed him to enter the character and immerse himself completely.
In the 1960s, Kemp founded his own theatre company The Lindsay Kemp Dance Mime Company. Some of his most famous works are *Flowers* (1974, based on *Our Lady of the Flowers*) and *Salomè* (1977).
Through the use of music and light, Lindsay Kemp pioneered a genre of dreamlike, almost acrobatic theatre known as *Cirque Nouveau*.
Kemp was David Bowie's teacher. He followed Bowie around, teaching him acting and stage control. It was the beginning of a collaboration that laid the foundations for rock theatre.
The theatre school of Italian mimicry also became relevant. Dario Fo [4], playwriter, actor, director, painter, writer, and set designer, was an example.
The great success of his plays is due to the effect the actor gave to the words through mimicry and gesture, making rhythm a fundamental part. Dario Fo writes in his *Manuale minimo dell'attore* [22]:

> Rhythm is the fundamental component of the relationship that the individual establishes with his own body in the articulation of movement.

We wanted to mention the history of mime theatre because it is fundamental to the study of movement and expression. Without the basic knowledge provided to us by this study, it would have been impossible to define a meaningful structure for our device. However, we do not want to create a robot with human characteristics. We want to build one whose movements resemble human gestures without being exact copies of them. We also find this type of representation in theatre, particularly in the plays of costumed mimes.
In the performances of the theatre company Mummenschanz [50] [Figure 2.3], the actors create dialogues and stories using only the movements of their bodies and invented masks and costumes that cannot be traced back to human features. Through body language, all performances are said to have a *universal language* as they are understood internationally.

Figure 2.3: Scene from a play by the Mummenschanz company

La Commedia dell'Arte

The type of theatre play known as *La Commedia dell'Arte* originated in the Italian theatre between the 16th and 18th centuries and is an example where movement becomes an integral part of the performance.

Each role is associated with a personality, and during the performance, the actors must be able to link the movements with the desired emotion, but also to decide on the rhythm according to the personality to be played [Figure 2.4a].

In the case of the interpretation of the role of the servant Harlequin, when the character is talking to his master or another character of higher rank, the actor shows submission by leaning forward and backward, lowering his voice, keeping his gaze low, and making slower and more careful movements, while when talking with his comrade Brighella is always making a kind of dance [Figure 2.4b].

Therefore, the use of specific physical shapes and movements for each character in Commedia Dell'Arte can be considered an early form of shape language in character design. For example, we can define differences in posture [38]: The doctor has a backward bent posture, shows his belly to the outside, and walks with heavy movements; Pantalone has a stooped posture, and bends forward, his hands are on his hips or in front of him as if to indicate something; Brighella keeps his hips closed, while Harlequin has open hips and a playful posture.

Exercising on the characters of the Commedia dell'Arte is still one of the main steps of many actor formation schools.

(a) Commedia dell'Arte characters

(b) Movements of the Harlequin character

Figure 2.4: Two representations of Commedia dell'Arte characters

Figure Theatre

The study of figure theatre was of fundamental importance to the development of this thesis. We used the concepts of this art to explore the various techniques of live animation of puppets so that they could be reinterpreted and used for the structure and movement of non-autonomous but remotely controlled robots.

The term *figure theatre* [59] was coined in the 1970s. At that time, the art form was known as *animation theatre*. Between the 60s and 70s *theatrical animation* [58] was developed. It was defined as a set of practices to educate children and young people. To avoid confusion with the term 'animation', the term 'figure theatre' was introduced.

Figure theatre [45] refers to all forms of live performance that use artificially animated objects and figures during the performance. Forms such as marionettes, puppets, shadow puppets, and even more generic objects are part of this movement.

Figure theatre, or animation, originated in ancient Greece between the 8th and 7th centuries BC, even before actor's theatre, and was used for religious functions.

The first documented form of figure theatre was the marionette. It was half-busted and hollow puppets, so the puppeteer could put his hand inside and animate the figure directly.

From the Middle Ages, this type of theatrical art became the prerogative of street performers, who began to use dismountable theatres consisting of a cloth and two columns.

The first puppets date back to the Middle Ages. They were made as mechanical wooden figures with movable limbs. The first appearance dates back to a historical event in Venice in the church of Santa Maria della Salute. Every year, the church held a procession to select four girls from the crowd; the wooden figures were made to prevent riots during the selection. Marionette comes from *Mariona*, named after the Church of Santa Maria della Salute. During the processions, miniatures of the Marione were made and sold in the stalls. They were called *marionettes.*

From the middle of the 17th century, these puppet and marionette shows became performances that were also performed in theatres and for higher-class people. This favored the development of Baroque theatre.

The difference between the usability of puppets and marionette shows lies in the running costs. Puppet companies were smaller and had lower running costs, making them more popular in smaller towns. Marionettes require a larger budget due to all the facilities needed for materials and stage set-up, so puppet companies became rarer and appeared in inner-city theatres.

In modern times, figure theatre has evolved significantly [17]. Different materials began to be used and manipulated in different ways. Some examples are the mise-en-abîme, where puppets are used in performances with actors; the marionization of actors (present in the works of Totò); the use of mannequins such as in Tadeusz Kantor's opera *The Dead Class.*

Writing for puppetry is very different from writing for an actor's show and needs to be mentioned. Puppet shows must have straightforward dialogues, so the interactions will be quick but meaningful, mainly characterized by movements. Puppets replicate human postures, but as they are not persons, they can bring on stage concepts defined as *non-human* (life and death, body as object, etc.).

Figure theatre also developed in the East. *Bunraku* [29] was born in Japan, in Osaka, in 1684. This theatrical art uses very high puppets, more than half a person, maneuvered by puppeteers present on stage, dressed in black and in silence [Figure 2.5].

At least three people are needed to maneuver a puppet of this size. This art requires synchronization between all the people involved in the performance, not just the puppeteers on stage. To move a single hand of the puppet requires at least twenty years of study. The movement of the head is only assigned to experienced manipulators. Due to its complexity and stage performance, this type of theatre art is considered one of the most important in the world.

Figure 2.5: Japanese marionette in traditional Bunraku opera

Modern Puppetry

The evolution of technology has led to the construction of increasingly complex mechanisms. Theatre comes to take its cue from robotics and vice versa. One example of this collaboration is the Coppelia Theatre company [13].

This company was founded in Siena in 2010 to introduce engineering characteristics into figure and performance theatre. Their theatrical engineering project is to create multimedia and scenic works with wrist puppets.

Siberian engineer Vladimir Zakharov Yakovlevich was the inventor of these particular puppets. He made the prototype around the end of the 1990s. Jilenia Biffi is the creator of the wrist puppets for the company. She studied directly with Yakovlevich in Siberia and decided to bring this innovation to Italy.

Wrist puppets are particular because they are attached directly to the hand and forearm of the manipulator using an iron frame. The manipulator's wrist controls the head, while the eyes and hands can be controlled using more articulated control levers. The puppets' hands are highly articulated because they are made to be prehensile. All the mechanisms of each puppet are made by hand. However, the time required to learn how to operate them is longer than the time needed to build them.

Their project *Trucioli* is an example of a stage play that can be transposed into a multimedia work (chamber theatre) as if it were a short film [Figure 2.6]. This is part of the company's debut show, Due Destini. In this work, you can see how the joints are constructed to allow fluid and natural movements. The proportions of the figure are specially designed to make the scene as truthful as possible.

Figure 2.6: Wrist puppet image from the opera *Trucioli*

Modern figure theatre also leads to having the manipulator as an actor present on stage with the puppet.
With Joan Baixas [57], the term *visual theatre* was born. For Baixas, the focus is not on the actor or the marionette but on the animation itself as an action that is performed thanks to an intermediary (the manipulator or the prop). With this conception, the interaction on stage becomes even more important and meaningful.
One of Baixas' students is Marta Cuscunà [15], an actress and manipulator of puppets and props. She explores the potential of the movement of mechanical bodies on stage. She brings to the stage particular marionettes called animatronics [14] [Figure 2.7].
Cuscunà introduced contemporary technologies for movement, materials, and industrial components to construct stage objects. Using mechanical joysticks, the puppeteer can move levers and cables to control the puppets on stage.

Figure 2.7: Marta Cuscunà with two animatronics from her work *The elegy of the fall.*

2.1.2. Dance and ballet

The study of movement in dance is fundamental, as it is comparable to a theatrical performance with non-verbal communication.
In ballet, the Vaganova and Balanchine styles are well known [54]. The Vaganova style

is mainly used in Russia and Eastern Europe. It is known for its delicate movements, well-defined and technically clean poses. The Balanchine style is used in the School of American Ballet but can be found in many schools around the world. It is characterized by fast, clean, and rhythmic movements.
In both methods, the interpretation of the role on stage is fundamental, although it is taught in different ways. The dancer must feel and trace movements as wide as possible to emphasize the emotion of the scene. An example where the interpretation of suffering can be studied is the excerpt of the death of the swan in the opera *Swan Lake* [55]. In this piece, the performing dancer moves her arms in increasingly fast and jerky movements to emphasize fear and hysteria and then slowly collapses on stage.
Rudolf Laban was a movement theorist, a choreographer, and a dancer. He defined the Laban Method [20] [Figure 2.8], which breaks down a movement into four characteristics:

- Direction
- Weight
- Speed
- Flow

Each characteristic is further divided in two:

- Direction is either direct or indirect.
- Weight is either heavy or light.
- Speed is either quick or sustained.
- Flow is either bound or free.

He later combined these classes in efforts to create the *Eight Efforts*:

- Wring
- Press
- Flick
- Dab
- Glide
- Float
- Punch
- Slash

Each effort is defined by the combination of the various degrees of action described above. This methodology is still used today in the teaching of the performing arts because it allows the actor to identify with an action both physically and emotionally.

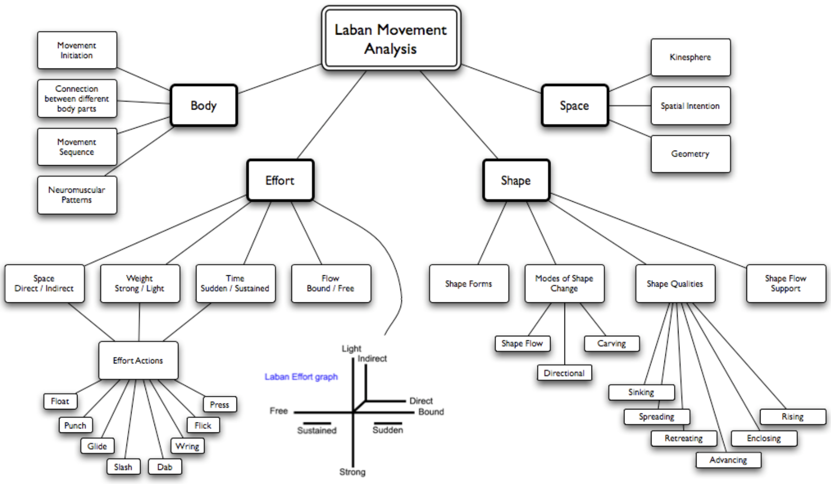


Figure 2.8: Diagram of Laban's methodology for dancers

This method has also been used to define the movements of a robot. H. Knight and R. Simmons [31] identified a set of main motion features derived from the Laban method. These features allowed the researchers to analyze and generate expressive movements using only three degrees of freedom. These are position (x, y) and orientation (theta). Efforts are parameterized in the three variables and represented in specific trajectories derived from robotics and theatre studies. The results of this study state that the movements of a robot defined by the Laban method are comparable to those of a person. This confirms the importance of studying movement as a prerequisite for constructing an expressive robot.

2.1.3. Animated films

The concept of animation can be found in other fields, and not only in the puppet theatre. We want to mention the new studies concerning the animation of fictional characters in animated films and cartoons. We used the concepts we learned to understand what is required to make a fictional character 'real'. These concepts were helpful in both the development of the structure and the programming of the robot's movements.

Character design

Character design is used in the creation of fictional characters. Early Disney animators developed various techniques [52] to shape the characters in an animated film and to make them appealing in the eyes of the audience.
Walt Disney first stated that to make characters as captivating as possible, it was necessary to define relevant personality and physical appearance. This was at the heart of the animation of the Seven Dwarfs in the Snow White film. Each dwarf has a personality that perfectly matches their physical appearance and movements.
The actions performed by a character define his behavior. To make the illustration realistic, Disney suggested to animators successions of everyday activities easy to understand and not extravagant. This helps us to understand that to define a personality, a general character type must be chosen. It has to be consistent with the story one wants to tell. Subsequently, nuances are added to enrich the story.
The animators had to study every aspect of the character before portraying it. They have to like the report that has been done on this role. What kind of person is he? Is he irascible? Is he happy and extravagant? Etc. In programming the movements of a robot, this concept is also relevant. The robot can move in different ways, for instance, by changing speed or keeping it constant, stopping abruptly or gradually [46].
We can use the animation concepts and transpose them into the programming of a robot. In this case it is not the movement itself that will be important, but how it is made and perceived by the people interacting with the robot. Animation in human-robot interaction is divided into two parts.

1. Use of animation techniques to define how a robot moves. In this case, it is also relevant to define the style of the robot. Style means the robot's behavior and the expressiveness of its actions.

2. Understand how this action is perceived by the person interacting with the robot. The aim is to make it appear as if the robot has its personality and to make it easier for the person you are interacting with to understand what the robot is trying to do.

Costumes are another character's trait and help to define their role and the behavior expected of them. The color of the clothing and the design make the character a specific individual. The concept of clothing is also applicable in our case. The robot's clothing must be as consistent as possible with the role it is to play.
Another aspect of the animation process is the sequence of actions. During the drawing of the character, so-called thumbnail drawings are used [Figure 2.9]. These emphasize each

step of the character's movement and make it possible to see how each body part moves and at what instant. The individual steps are defined as acting symbols and must be easily identifiable by the audience. We used this technique in the drawing of the robot's movements. It allows a visual representation of the angles to be given to each motor at each moment to realize a given position.

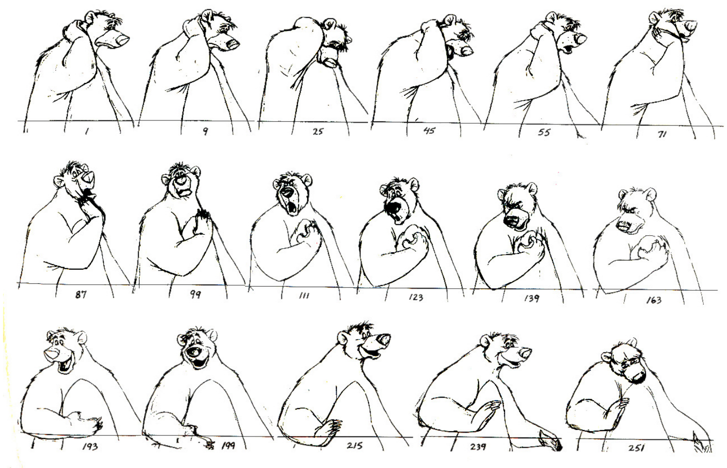


Figure 2.9: Example of a thumbnail drawing made by Disney's illustrators

Disney's fundamental principles of animation

The construction of an animated character involves defining its role and its actual animation.

By animation of a character, we mean the design and how his body acts, reacts, and changes during the scene.

Over time, Disney animators have defined twelve cardinal principles of animation [52]. They created these rules by drawing and testing theories on a half-full sack of flour, drawing a configuration of the object for each emotion [Figure 2.10].

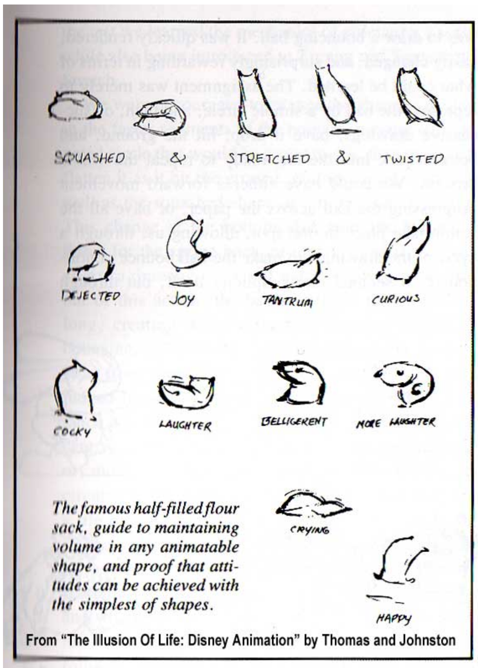


Figure 2.10: Different poses of the animated half-full sack of flour made by Disney's illustrators

These rules help to relate drawings of a moving character to each other and to achieve a consistent result.

1. Squash and stretch

   A character can be squashed or stretched but must never lose its recognizable features. In this way, every line of the body becomes relevant. For example, a smile is not drawn as a simple curved line. It is related to the lips, cheeks, and proportion of the face. These observations can be made for every part of the character's body. The transformation phases of a body during a movement were tested using a bouncing ball. In this example, one can see how the ball stretches or contracts as the action progresses.

2. Anticipation

   The audience cannot understand an action unless the movements are well-defined in advance and linked together. The audience must be prepared for each gesture before it happens

   In animation, it is essential to put a secondary action before the main movement that suggests what will happen. This action can be of any kind, smaller or larger, but it must let the concept shine through.

3. Staging

Staging means presenting an idea in a clear and not confusing way. An action must be designed to be understandable, a personality and expression must be recognizable, etc.
The main point is to keep the story in mind. A character must maintain his attitude throughout the work. For example, a female character must always be portrayed with consistent stances, even if she is overreacting to something.

4. Straight ahead action and pose to pose
   This difference regards two different approaches to animation. In straight ahead action, the animator draws each frame considering the action to be performed by the character, but without knowing the details. The drawing is done position by position sequentially, but the content of each frame is decided at the moment without a predetermined idea. In this case, a more spontaneous action is achieved.
   In pose-to-pose, the animator draws the action in every aspect. The illustrator plans the movement, decides which frames are needed, and creates the drawings by relating dimensions and poses performed by the body. A second person is then responsible for drawing the intermediate steps between frames. With this method, the resulting action is clear and consistent.

5. Follow through and overlapping action
   Before this guideline, when a character finished his action, he would stop completely. This was unnatural and made little sense. These techniques were created to solve this problem. Although they are two different methods, they are closely related and often used simultaneously. Five categories can be distinguished.

   - The extremities of a character move even if the character is stationary.
   - The body does not move all at once, but the various parts must be distinguished.
   - Soft body parts (cheeks, belly, etc.) move at a slower speed than skeletal parts.
   - The way an action is performed says more about the character of the character than the action itself.
   - Moving hold. This is the opposite of follow through and moving forward. It is implemented when a character is about to act and needs to convey a state of mind. The design remains the same for several consecutive frames so that the viewer fully grasps the character's attitude at that moment. For it to be applicable, the process of creating that frame must be precise and studied in detail.

6. Slow in and slow out
   The topic of deliberation is the augmentation or retardation of actions. Not all individuals advance and end their motions at the same velocity. Every action and emotion is linked to a rate of motion.

7. Arcs
   To construct a lifelike and authentic gesticulation, the action of human extremities has been examined. Movements are not delineated by lines but by curves. With this technique's implementation, grids and points were also incorporated into the scenes, not just basic postures.

8. Secondary action
   Effectuating a primary action can be reinforced by utilizing secondary actions of the body. The complexity resides in being able to synchronize the primary action with the subordinate ones so that it persists unmistakable which is the principal one. Facial expression can be a secondary action.

9. Timing
   The number of movements in a given action determines the time taken by a character to act. This affects the work from two different angles. First of all, the design is simple, it's clear, and it's easy to tell a story. Second, the time of the action can affect the emotion of the character.

10. Exaggeration
    Disney's approach to achieving realism in its characters involves exaggerating their features; for example, if a character is meant to be sad, they should be drawn in an even more despondent manner than initially thought.

11. Solid drawing
    Animators must possess the ability to draft the character from all perspectives for it to be easier to envision actions and conduct. To accurately render the character, one must be aware of the accurate proportions and mass of the sketch. Artists should be adept at crafting solid, three-dimensional illustrations.

12. Appeal
    This concept is understood in its most expansive interpretation. That is, any attribute an individual might want to observe in a character (charm, attractive design, straightforwardness, communicativeness, and magnetism). A character must convey and assert its role, persona, and value in the tale.

Robot animation

The notions related to the animation of drawings and fictional characters can also be applied to structures and automata.
Remaining in the film industry, animation's concepts on physical structures such as animatronics are used. These devices are mechatronic puppets used as real actors in television, theater, and even theme parks.
The principles of animation are also adaptable to the sector of social and interaction robotics.
The research called *The Illusion of Robotic Life* [40] was carried out by T. Ribeiro and A. Paiva. They applied the twelve basic principles of animation to two social robots, NAO and EMYS.
NAO is a bipedal robot developed by Aldebaran Robotics with a human-like shape but no facial movements [Figure 2.11]. The principles taking into account the gestures of the whole body were applied to him.

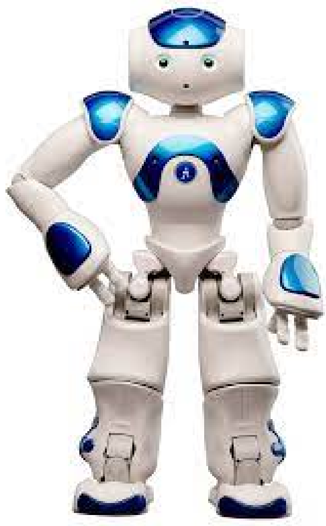


Figure 2.11: NAO robot

EMYS, developed by FLASH Robotics, consists only of the head and neck [Figure 2.12]. It has a wide range of facial expressions and fluid movements. The techniques applied to this robot concern only the face.

Figure 2.12: EMYS robot

Here are the most important considerations for each principle:

1. Squash and stretch
   This principle concerns the possibility of a body in an animated film to deform. This rule is difficult to apply since robots generally consist of rigid parts.

2. Anticipation
   Anticipation can be used in managing a robot's movements to make iteration more natural and enjoyable.
   In the NAO robot, this principle is applied by adding the stretching of the body before a jump. This produces a propulsion that the robot appears to generate for itself.

3. Staging
   Staging is about building the scene around the character's acting. We can apply this principle to robots through multi-modal expressions, lights, and sounds.

4. Straight ahead and Pose-to-Pose
   This straight-ahead technique permits the illustrator to determine the action steps instantaneously as each frame is generated. Moreover, it can be utilized to control a robotic system by managing its sequence of movements interactively and procedurally.
   Utilizing the Pose-to-Pose process, the illustrator must deliberately determine every motion of the character on a sequential basis. In robots, it is possible to implement

this principle using pre-designed gestures and combining them with other behaviors or actions.

5. Follow-through and overlapping actions
   Regarding the conclusion of an effort, a protagonist should not end the motion abruptly. It should instead taper off momentum slowly or rapidly. This will make the action more naturalistic.
   This principle can be applied to robots without any modifications. Changing the speed at which an action is completed gives the impression of fluidity in the robot's movements as if it were part of our natural world.

6. Slow in and slow out
   These principles relate to the correlation between two motions. The progression from one manifestation to the other must be progressive. Thus, the silhouette and the movement acquire different shades additionally associated with the tempo of execution.
   In robots, this is one of the most relevant principles that can be applied. This can be achieved by synchronously changing the speeds and angles of the motors and by blending different positions.

7. Arcs
   To be recognized as organic, movements must be curved, not linear. To illustrate, rather than traveling from right to left horizontally, the head should slightly rise throughout the motion, thus giving it a rounded completion.
   This principle can be used with robots in all types of animation by moving multiple motors simultaneously.

8. Secondary action
   This does not portray any sentiment but solely enhances the motion.
   Its incorporation in robots could include the addition of winking of eyes or slight oscillatory motion of the body to duplicate respiration.

9. Timing
   Animation incorporates the timing of a character's movements. The length of the action is dependent upon multiple factors, for example, the environment and the feeling the character seeks to display.
   This importance of timing is especially pertinent for robots, as it allows the same action sequences to be altered in rhythm to produce different emotions.

10. Exaggeration

This concept is grounded on the premise that animated characters are exempt from the laws of physics as we comprehend them. As a substitute, they must exaggerate their movements to make their intentions unmistakable at a specific juncture. Amplifying the gestures can accentuate the robot's activities to render them persuasive.

11. Solid Drawing
    Three-dimensional drawing is generally associated more with character design than with animation, and it is also helpful for illustrating the poses a robot will take. These poses mustn't be flat and neutral but rather asymmetrical, creating movement even when the robot is inactive.

12. Appeal
    The desirability of a character is based on their appearance. To effectively convey the idea of the character, this must be depicted in a particular manner.
    The singular movements, and more generally, the sequences enacted by a robot, must be clearly comprehensible. If a viewer does not understand what a character is doing, they can quickly lose interest.

In the production of both the structure and the motions of the robot developed in this thesis, these principles were utilized. Particularly, five of these rules were taken into account: follow through and overlapping actions, arcs, exaggeration, secondary action, and appeal.
Given the exclusive nature of the issue, it was not essential to fully deploy all the principles. As the robot must be completely managed, the need to program the movements and manage their timing is no longer necessary.

Shape language

In animation, kinesics is combined with the study of forms. In a cartoon, mainly those aimed at children, the role of the characters must be immediately understandable at first glance. Shapes and proportions help to make a particular role or emotion comprehensible. This type of study is called *Shape Language* [36] and is used in many artistic fields like drawing, design, illustration, and cinematography.

> When used in character, object, and background design, shapes can tell a story, show personality, and elicit an emotional response in the viewer without using any words.

There are five basic types of shapes in the language of shapes:

- Circles

- Squares
- Triangles
- Spirals
- Crosses

Each represents different characteristics that can be associated with the character. For example, a main character in a story, if considered friendly and robust will have a spherical body shape or a square one but with rounded corners. A triangular, angular shape, typical of antagonists in a story, will never be associated with a good character.
The theory concerning the shape language was developed in theatre. In particular, the Commedia dell'Arte plays a fundamental role as a precursor to the use of body shapes to represent the different characteristics of a character [38][Section 2.1.1]. Each character is associated with a form, and the actor must follow it in interpreting movements. For example, Balanzone (the doctor) has a rounded, circled shape associated with the letter 'O', also known as the O-shape. In his case, the movements are bouncy and wide. The actor must always keep his torso tilted back to show his belly, and his knees must be slightly bent. The arms should follow the body's movement fluidly and comprehensively while remaining bent and with the hands on the belly.
Animated films feature characters whose intentions and dialogue can be understood even though they are mute or express themselves through speech. Here we list three examples of existing cartoons that we used as references during the thesis development.
Wall-E© *Disney* is one of the most popular animated films in which the main characters interact with each other not through speech but through gestures and looks [Figure 2.13]. To the eye of a viewer, the roles and dialogues are understandable thanks to the shape and movements that the directors have designed for each character.

Figure 2.13: Scene from the film *Wall-E*© *Disney*

In the film *Treasure Planet*©*Disney*, the study of shapes and movements to define an intention was consistently used in the character of Morph [Figure 2.14]. This secondary character plays the role of the main character's helper and therefore has a rounded and abstract shape. Each emotion is linked to a particular body position, pupils, and mouth.

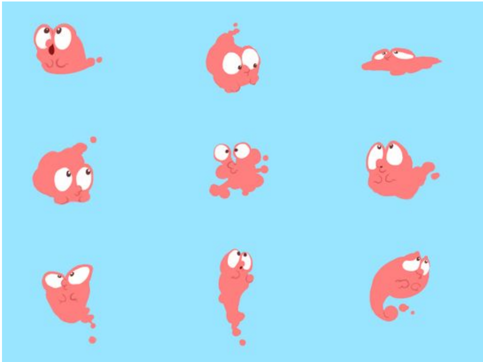


Figure 2.14: *Morph*©*Disney* different emotions

Another example of a fictional character is *Snoofs* [33]. In this case, it is a picture book in which characters express themselves using body shape, body positions, and facial expressions focusing on eye and mouth positions.

2.1.4. Exhibition arts

We would like also to mention artistic works in which the study of emotions and how they can be shown through shapes, materials, and movements is fundamental. Painters and sculptors have always struggled with shapes, colors, and facial and body expressions, some with realistic figures, others with more abstract ones.
One noteworthy artist is Yayoi Kusama, the "polka dot artist" [71]. By using colors and surfaces, but always keeping the same texture she represented different scenarios and moods.
Using kinematic mechanisms and everyday objects, Tobias Bradford [7] creates works in which rhythm is essential to convey the idea of a mood to the viewer.
The 'dancing banners' from Technofrolics Exhibition [51] is a creative piece that seeks to evoke an emotional response from its observers. This set-up consists of spandex and lycra sheets affixed to latex backings. The elastic material facilitates seamless motions. The latex base prevents the sheets from warping or tangling during high-velocity actions. Both extremities of the sheets are managed distinctively; the first is controlled by brushless servo motors that are computer-governed, while the second is either autonomous or linked to externally regulated brakes. The torsion level of the banners can be controlled

manually. The system is tied to a graphical user interface, which permits external control of the choreographies.
This system allows you to express emotions and moods with your choreographies. These can follow background music, a narrative voice, or move according to their rhythm. Interest turns to the sequence and speed the sheets assume during the performance. The changes in rhythm and position of the sheets generate a mood to make the sheets as expressive as possible.

2.2. Avatars and communication

This section introduces the concept of an avatar, which is necessary to understand the motivations for this project.
By definition, an avatar is [9]:

> a character or creature created by you to represent yourself in a computer game, on the internet, etc.

To be an avatar, then, is to step into someone else's shoes to represent the actions and thoughts of the person in charge of the body.
The avatar concept is present in all online games, where the player must choose a character who will be his *pawn* during the game. This concept is also applied in figure theatre. In particular, as mentioned in the section before, commanding a body with one's movements is used in puppetry. The puppeteer is an artist capable of moving and voicing puppets so that they have realistic dialogues and seem alive in the eyes of the spectator.
One virtual environment that has become increasingly popular in recent years is the Metaverse. By definition, the Metaverse [39] is:

> a virtual-reality space in which users can interact with a computer-generated environment and other users

A user can enter the metaverse through a VR visor and interact with others through virtual alter egos created at the user's will. A virtual avatar can be generated in the image of its owner, or a user can choose to completely distort their form and take on the appearance of others. The idea of avatars in a metaverse has been made well-known by Neal Stephenson in his cyberpunk novel *Snow Crash* [49], where people can live in the real world or the Metaverse through their avatars. The idea then inspired the Second Life network platform [61] and the present Metaverse effort by Meta.
In general, the person controlling their alter-ego must be able to exploit the full potential of the body they are using as if it were their own. In this way, it is possible to express

oneself clearly. The ultimate goal of constructing an avatar is to be able to communicate with one's interlocutors by appearing natural and deceiving them, making them believe that the body they are interacting with has a life of its own.

2.3. Robotics and contexts of implementation

The main aim of this project is to develop an expressive robot. In this section, we want to define what a robot is and what are the areas of application of this technology. Subsequently, the discussion opens on the expressive and interaction possibilities that the structure can assume.

2.3.1. Definition and history

The etymology of the word *robot* [68] comes from the Czech word *robota* which means "slave labor" or "corvée". This term indicated the fixed period of unpaid work in the service of a master.

The first person to use this word was Karel Čapek in his book *R.U.R (Rossum's Universal Robots)*, published in 1920. This story opens with the presentation of a factory of creatures with human features. These beings were used to perform manual labor in place of men. They are described as emotionless, incapable of thinking, and uninterested in self-preservation.

The term *robotics* [65] was later coined by the writer Isaac Asimov. This word refers to the field of study concerning the construction and programming of robots. Asimov also creates the *Three Laws of Robotics*, a repeated concept in his works.

1. First Law
   A robot may not injure a human being or, through inaction, allow a human being to come to harm.

2. Second Law
   A robot must obey the orders given to it by human beings except where such orders would conflict with the First Law.

3. Third Law
   A robot must protect its existence as long as such protection does not conflict with the First or Second Law.

These regulations have undergone various changes, yet they remain fundamental to the introduction of these types of devices.

A robot is a programmable device capable of performing sophisticated tasks. These devices can be fully autonomous, semi-autonomous, or fully controlled:

- Fully autonomous

  Autonomous robots can act without human intervention [62]. The first two were introduced in the 1940s by William Gray Walter; they were called Elmer and Elsie, and were programmed to think like a biological brain and with free will. They were capable of phototaxis, i.e, reacting to light pulses through movement.

  The fundamental characteristics of an autonomous robot are:

  – Self-maintenance

    The robot must possess a certain degree of self-sufficiency. For example, to be defined as autonomous, battery-powered devices must understand when the battery is running low and find their charging station.

    This concept is based on *proprioception*, or the ability to sense one's internal state.

  – Sensing the environment

    In this case, we can talk about *exteroception*. Robots must have a series of sensors that allow them to sense and interact with the external environment. These machines can detect malfunctions and minimize their impact on performance.

  – Task performance

    This characteristic concerns the robot's ability to complete the task for which it was created regardless of external conditions. An example is domestic robots that must be able to navigate within a new and non-ideal environment.

  – Autonomous navigation

    How a robot explores its surroundings depends intrinsically on the environment in which it is placed. In the case of a closed environment, the device needs to know where it is within the space. This can be achieved in two steps: localization and mapping. Localization lets you know where you are in an instant of time and allows point-to-point navigation. Mapping allows the robot to know the entire space in which it is located as if it had a map of the environment in memory.

    In the case of an open environment, a distinction must be made between air and ground navigation. Air navigation is manageable due to the rarity of obstacles and is used for drones or missiles. Ground navigation concerns land vehicles and takes on various complications (three-dimensionality, density, meteorological conditions, and environmental instability).

Autonomous robots are becoming increasingly popular, and the fields of use are vast. Some examples of these devices are space probes, social robots, and military equipment.

- Semi-Autonomous
  It is difficult to distinguish between autonomous and semi-autonomous robots [48]. Semi-autonomous robots accept commands from other systems or users. This type of device is more common than fully autonomous machines because it is based on the idea that those who buy a similar object will want to control it as they wish. An example of semi-autonomous robots is vacuum cleaners. They accept general commands from a user, such as start and stop, but are autonomous in carrying out their work.
  In semi-autonomous robots, there is always the proprioception characteristic, but it is weaker. For example, when the device detects a low battery level, it no longer needs to return to its charging station on its own but can notify the user.

- Fully controlled
  Robotic devices that are fully directed lack the capability for self-repair and can not explore the surroundings [64]. Such mechanisms will not operate without a user or system controlling them.
  Guided robots are used in many industries. This is especially true for tasks that necessitate a skilled operator yet can be enhanced by technological advances. An example of a fully controlled robot is the *Da Vinci*, used in the medical-surgical field for laparoscopic operations. The surgeon has complete control of the device. It consists of a robotic arm and a camera. The control station allows the surgeon to see through the camera and operate remotely using hand controllers.

Although robots as we know them today were defined in the 1920s, the automaton concept dates back to antiquity. In ancient Egypt, Greece, and China several documents have been found that prove the invention of autonomous machines. These devices were created both to facilitate manual work and for leisure moments.
The first remotely controlled devices date back to the late nineteenth century. In particular, different types of remotely controlled torpedoes (submarine weapons launched just above or below the water surface) are created. In 1903, engineer Leonardo Torres Quevedo used a radio control system to command an airship.
The first humanoid robots defined according to Čapek's idea date back to 1928. In that year, Eric, a human-like robot built by W. H. Richards, was presented at the Model Engineers Society exhibition in London. It consisted of an aluminum body, eleven electromagnets, and a motor powered by a twelve-volt battery. He could move his head and

hands and was controllable remotely or vocally. In modern times, the use of robots has become increasingly widespread, covering more and more sectors. Today, there are different types of robots, each with its own characteristics depending on the area of use. Some examples are mobile, industrial, educational, interactive, social, modular, and collaborative.

Our project is focused on social interaction, which is why we took inspiration from categories of social and interaction robots.

2.3.2. Social and interacting robots

A general definition of social robots can be [5]:

> Social robots are artificial intelligence platforms, paired with sensors, cameras, microphones, and other technology, like computer vision, so they can better interact and engage with humans or other robots.

In general, social robots are devices that allow you to create an interaction and exchange of information between themselves and another agent. They can communicate and understand the moods and intentions of those interacting with them, using different ways depending on their structure.

Social robots are used with children and adults without limitations. They can keep you company or be an emotional and educational support. For example, these robots are often used to help the growth of children with autism or to provide support to patients with dementia. We also find these devices in the tertiary sector, as customer services to customers of a shop, guests of a hotel, or visitors to an exhibition.

These devices do not necessarily have a human appearance but can be of different shapes and sizes depending on their use. Here are a few examples of social robots:

- FURHAT
  Furhat Robotics designed and developed the "Furhat" robot [24] to be completely adaptable by the customer. It has a structure that resembles the human neck and head. The face supports a back-projection system that allows the image of a digital face to be shown on a physical mask with human features. This combination of hardware and software gives the flexibility of a digitally animated profile on a realistic, physical structure. Everything is customizable: skin color, voice, language, age, and gender. Facial expressions are studied to be natural, including gaze and uncontrolled movements (blinking, micro-movements of the face, etc.). This robot can also have more than one interlocutor. Thanks to computer vision techniques, it is possible to identify and converse with all the interacting agents.

- JENNIE
  JENNIE [53] is a robotic dog created by TOMBOT. It is used to support people with cognitive and social problems and can be used to relieve stress, depression, anxiety, and loneliness. This robot has been specially developed with a hyper-realistic appearance and behavior. To achieve this, the structure was commissioned by an animation company usually working for the cinema. The electronics include pressure sensors all over the robot's body so that it reacts immediately to touch. Jennie recognizes voice commands and can make sounds (realistic recorded by a labrador puppy). It can also be controlled via a smartphone application.

- Greeting Machine
  This is a non-human-shaped robot designed by the Interdisciplinary Center (IDC) Herzliya [2]. The objective of this study was to demonstrate that even a robot with limited degrees of freedom can effectively interact with another person. The robot's purpose is to communicate positive and negative social cues in the context of opening encounters. The structure consists of a sphere on which a smaller ball rotates. The movements were designed in collaboration with experts and tested with individuals.

- Sophia
  Sophia [26] is a social robot made by Hanson Robotics. Its structure has been designed to be hyper-realistic and is used as a conversational agent. It was created to provide support in areas such as medicine and education and for artificial intelligence research. Sophia is a full-body robot designed to mimic the human body, able to move its arms and legs. The face is covered by a material that resembles the texture of skin. Sophia's AI combines cutting-edge work in symbolic AI, neural networks, expert systems, machine perception, conversational natural language processing, adaptive motor control, and cognitive architecture. For this reason, its answers are always different for each situation or interaction.

- Ameca
  Engineered Arts created Ameca [19] as a development platform for social robots. An important feature is modularity, which allows each component to be managed and used as if it were independent from the rest.
  The structure was created to make movements fluid and lifelike.

Appeal of a robot

As we previously mentioned, a social robot can have different shapes more or less reminiscent of human appearance. It is a prerequisite for these robots to draw a person's focus and urge them to engage. The bodies must be designed to arouse positive emotions and curiosity, avoiding creating mixed feelings or even disgust.
Robotics professor Masahiro Mori introduced the concept of *Uncanny valley* [8] in the 1970s. Mori's hypothesis is based on the fact that as robots appear human-like, they become more attractive to people, but up to a certain point. When the similarity becomes almost total, feelings of strangeness and discomfort are generated in the viewer, accompanied by fear.
The Uncanny Valley is characterized by an individual's adverse sentiment toward particular robotic and automata systems.
This theory is illustrated following a graph [Figure 2.15]. The x-axis represents the similarity of a robot to the human form. The ordinate axis represents the feeling of appeal that the observer experiences at the sight of the robot.

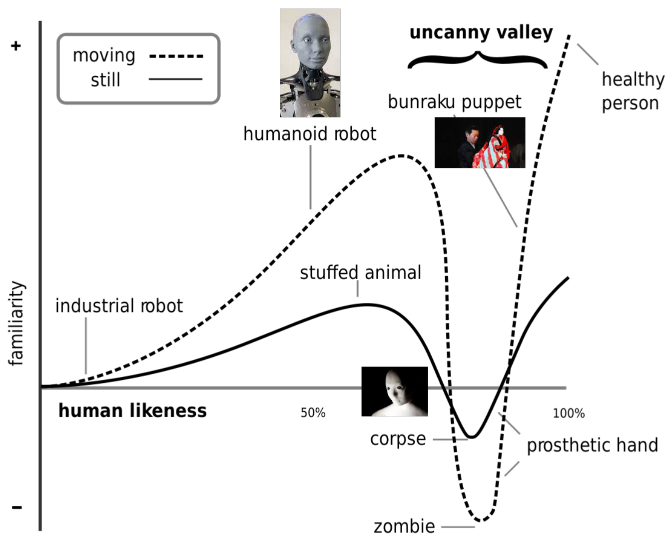


Figure 2.15: Uncanny valley graph

It can be seen that industrial robots are indifferent to the sight of people, and no emotional involvement is generated. The first to create a positive trend regarding appeal are robotic toys. This study was done on both children and adults. The tendency of the curve is generally subjective. The fact that in the graph shown here, the games are at a low level of appeal does not mean that, in general, every toy generates little attraction in every individual. The critical zone is between 70% and 90% similarity to the human

body. They are all those bodies that want to be hyper-realistic but are not realistic enough to emulate the human figure. They are all those bodies that want to be hyper-realistic but are not realistic enough to emulate the human figure. An example can be found in cinematography. Incorporating computer-generated imagery has resulted in the fabrication of anthropomorphic personas, which may seem peculiar to the viewer. Let's consider the animated film *Shrek* [11]. A study conducted on children showed that seeing the character Princess Fiona caused a feeling of anxiety and fear. Another case was that of the film *Cats*, in which CGI was used to transform the actors into cats, but with human movements and faces.
A feeling of inadequacy was also felt in several robots:

- Telenoid
  It is a robotic communication device created by Hiroshi Ishiguro [28]. Its structure resembles a ghost, and the neutral expression generates discomfort in the interlocutor.
- Diego-san
  It is a robot created to help parents understand the needs of a newborn [25]. The problem with this robot is that its expressiveness is underdeveloped, and its dimensions are too large for the purpose it wants to achieve.
- Sophia and Ameca
  The two social robots presented above have been developed and designed to cross the threshold of the uncanny valley [26] [19]. One problem concerns the materials and facial movements that in these two systems are not yet at a sufficiently appropriate level for complete emulation of the human body.
- Prosthetic hand
  Prosthetic limbs are also mentioned in this category [8]. Mori declares that upon initial observation of a prosthetic, one may not be aware that it is not an authentic limb; however, upon recognizing this, a sentiment of distress is evoked. For instance, when shaking hands, we may detect that the arm is frigid or not possessing the appropriate grasp.

The puppets typical of the theatrical art of Bunraku (mentioned in the section on figure theatre [Section 2.1.1]) belong to a high level on the appeal scale, exceeding the uncanny valley. This is possible because their movements are managed by expert actors who use specific theatrical techniques. The structure of the puppets is realistic, but not too realistic; it is the movements that make the difference in the perception felt by the public.
It is possible to avoid the uncanny valley when designing a robot. A fundamental princi-

ple is not to formulate characters that amalgamate contradictory qualities, for example, natural and non-natural or veritable and contrived. Another method is to link the robot's expressions to the tone of its voice and movements. The purpose is to identify an emotional state and have the device represent that state with the whole body. Close attention should be paid to facial expressions, eyes, and mouth. The appearance should not be neutral or appear fake.

2.4. Physical Metaverse

This dissertation project is part of the *Physical Metaverse* [21] framework. It is defined as bringing the concept of the virtual metaverse into the physical environment. The framework aims to create a structure that allows a person to wear and represent a body (avatar) different from their own in the real world. We can identify three modules that are interconnected with each other:

- Physical Avatar
  The physical avatar is represented by one or more robots with characteristics that differ from each other in size, shape, and ability to move. The robots can be of any shape, but not anthropomorphic. This allows us to explore how the person and the avatar interface with each other and their surroundings. The perception will inevitably be different but still immersive. We do not want to imitate the human sensor system. These avatars can receive signals from the surrounding world and act physically in it.
  The ultimate goal is to give people the experience of being inside a body, possibly completely different from their own, and still allow them to interact with the outside world.

- Control Interface
  The control interface deals with all the controls that can be used to control the physical avatar. The purpose of this module is to allow the person to control the robot by experiencing total embodiment. To achieve this, the controller will have physical feedback on his every movement so that he is aware that his actions are affecting the avatar. The inspiration for this type of feedback control came from an in-depth study of puppetry: the puppeteer moves the bodies and uses the weight of the objects he is moving to calibrate the force and speed of the movements according to the emotions he wants to convey.

- Embodiment Interface
  The embodiment interface maps the five senses in the human-robot interaction. To

fully immerse, the controller must perceive everything the controlled robot perceives. To achieve this, the richest three of the five senses are considered:

- Vision. It can be interpreted in two ways: first-person vision(the controller sees what the robot sees) or third-person vision (the controller sees the entire environment in which the robot is placed).
- Sound. It can come directly from the robot's body or a system in the environment.
- Touch. It can be re-mapped with a different tactile stimulus (such as vibration or pressure) and then transmitted to the person.

3 | Analysis and considerations

In this chapter, we want to introduce all the motivations that led to the decision of the final structure that was later realized.
We present the initial state of the project: the existing robots, their structures, and the strengths and weaknesses of each in terms of mechanics, movement, and proposed interaction.
We augmented our reflections on the state of the project with insights from the background of theatre and animation, looking for various mechanisms present in other contexts to achieve as smooth and lifelike movement as practicable.
During the robot design process, we produced several prototypes, each with merits and disadvantages that we took into account for subsequent designs. A key point for us was deciding how people would interact with the structure, how many and which attention points to include, and how to manage their movement.
At the end of the chapter, we will present a digression on the avatar concept and how it was used within the project about robot control and perception.

3.1. Project status and prototypes

The first prototypes were inspirational concerning shape, interaction, attention components, most relevant movements, and technical instrumentation.
The study of all these devices was necessary for the design of the robot.
The robots were constructed following a modular model as far as possible. At least two modules for each robot are present: a wheeled base and a different interaction structure for each robot. Each module is removable and reusable, containing all necessary circuital, control, and mechanical components.

3.1.1. Control and exchange of information between modules

The robots presented in this section were built or adapted to participate in the Physical Metaverse project. Components have been introduced to allow remote control of the robot's degrees of freedom.

Command communication between the controller and the robot takes place in two steps. From the control room, a message is sent via WiFi in key-value format to the computer on board the robot. This is in charge of remodeling the value of the message by mapping the received number onto an interval consistent with the range of movement of the robot's degree of freedom corresponding to the received key.
The message translated for the control system is then communicated on a serial line from the computer to the specific control board. This board is in charge of managing the required movement. Serial transmission [69] refers to the bit-by-bit communication of a message between two agents using a communication channel or computer bus. This communication is done via a data cable, which in our case is a USB cable between the onboard computer and the required module's programmable board.

Raspberry Pi

Each robot contains a Raspberry Pi (version 3 or 4) [42], which allows commands sent via Wi-Fi from the control room to be received and sent to the control boards of the various modules. A Raspberry Pi is a small single-board computer (SBC) that can be used for domestic and industrial applications. The required power supply is 5 V, and the hardware on the board includes:

- CPU (Central Processing Unit)
  Model *3 Model B* supports a 4× Cortex-A53 1.2 GHz, while Model *4 Model B* a 4× Cortex-A72 1.5 GHz or 1.8 GHz.
- ISA (Instruction set Architecture)
  The supported instruction architecture is ARMv8-A, common in both board models.
- Processor
  - BCM2837 Broadcom chip used in the *Raspberry Pi 3 Model B*. This processor features a quad-core ARM Cortex A53 (ARMv8) cluster.
  - BCM2711 Broadcom chip used in the *Raspberry Pi 4 Model B*. The structure is the same as the BCM2837 processor but uses an ARM A72 core. This has significant improvements in GPU features and makes this model of Raspberry faster than its predecessors.
- RAM (Random Access Memory)
  Both models have 1 GB RAM.
- Networking
  The *Raspberry Pi 3 Model B* is equipped with 2.4 GHz WiFi 802.11n (150 Mbit/s),

and Bluetooth 4.1 (24 Mbit/s) based on the Broadcom BCM43438 FullMAC chip. The *Raspberry Pi 4 Model B*, on the other hand, supports dual-band 2.4/5 GHz WiFi 802.11n, and Bluetooth 4.1.

- GPIO pins
  A forty-pin GPIO (general purpose input/output) header is found on all current Raspberry Pi boards. All pins present can be designated via software to be input or output pins and can be used for a wide range of purposes. The types present are many, such as voltage pins (5 V and 3.3 V]), PWM (pulse-with-modulation), SPI (serial peripheral interface), I2C (Inter-Integrated Circuit), serial (TX transmit and RX receive).

- Ports
  Model *3 Model B* supports four USB 2.0 ports, one HDMI 1.3 port, and one 10/100 Mbit/s Ethernet port.
  Model *4 Model B* supports two USB 2.0 ports, two USB 3.0 ports, a USB-C port for power, two HDMI 2.0 (micro-HDMI) ports, and a 10/100/1000 Mbit/s Ethernet port.
  Both models feature a MicroSDHC slot.

Since these boards are real computers, the software consists of an operating system. The Raspberry Pi Foundation provides a Raspberry Pi OS (also called Raspbian). This operating system is a Linux distribution based on Debian. The programming language used is Python.

Arduino

Commands sent from the control room arrive at Raspberry Pi. They are then translated and sent via serial transmission to the correct Arduino associated with the structure whose movement has been requested.
Arduino [3] is an electronic board equipped with a microcontroller. It is used for rapid prototyping, which is very useful if you want to implement projects involving the control of small components.
This type of board differs substantially from Raspberry Pi. Arduino is a board with a microcontroller-based architecture, with the program to be executed and stored in flash memory. It does not support an operating system, RAM, or other components typical of Raspberry. It was decided to introduce both modules to achieve effective communication. Raspberry allows easy handling of networking and higher-level functions, and Arduino is needed to interface with the motors. Low-level functionalities are not guaranteed to be

stable when managed by Raspberry.
The Arduino board model used on each robot is the *Arduino Mega2560*.
This board is based on the ATMega2560 microcontroller. It supports fifty-four digital input/output pins, fifteen of which can be used in PWM, sixteen analog pins, four UARTs (hardware serial port), a 16 MHz crystal oscillator, a USB port and power jack, an ICSP header, a reset button. The ATmega2560 features 4 kb (4096 bytes) of EEPROM, a memory that is not erased when powered off.
We have used this particular Arduino board because of the variety of pins it supports. This makes it possible to use the same board to control many components (sensors and actuators).
The microcontroller is pre-programmed with a bootloader that allows the program to be automatically loaded into the board's flash memory. These boards are programmable using the C++ language.
The nominal input voltage of this board is 7 V to 12 V, while the I/O voltage is 5 V.
This board is directly connected via PWM pins to the motors that move the different degrees of freedom of the robot.

3.1.2. Wheeled base

Each robot in this discussion can move in space. This movement is enabled by a base containing three omnidirectional wheels, three DC motors, and control boards that allow the transmission of signals from the microcontroller to the motor.
Two types of base are used, a larger and a smaller one. They vary according to the size and weight of the robot on which they are placed.

Circuitry and Motor Control

Both variants of the mobile base have three DC motors inside. Although the type of motor is different, the components required for control remain the same.
A DC motor controller is required for each motor. This component manages the rotation speed and direction of the DC motors by controlling the power supplied at the input.

Omni wheels

Omnidirectional wheels [66] have small discs (rollers) around their entire circumference. These discs are positioned perpendicularly to the turning direction of the wheel. This allows the wheel to drive forwards and backward, while at the same time moving sideways with great ease.

We used a triangular structure, with the wheels arranged in a circular pattern 120 degrees apart. This allowed movement in any direction using only three engines. The control was carried out on the velocity on three variables (forward, strafe, and angular), allowing to adjust all the possible movements that can be performed in space (forward and backward, right and left, rotation> non-holonomic movement). This control is defined as high level because it involves the movement of the three motors connected to the wheels in an aggregated way, not each wheel being controlled independently.

Small wheeled base

We have used this base for light and small-sized robots.
The base length is 430 mm, width is 380 mm, heigth is 100 mm. Inside it mounts three omnidirectional wheels of diameter length 70 mm. The engines are DC brushless motors, which can be controlled using motor control boards (10 Amp, 5 V - 30 V DC Motor Driver). The input voltage required for this type of base is 12 V.

Large wheeled base

We have used this base for heavier robots that are taller in size and need stable balance [Figure 3.1].
The base diameter is approximately 500 mm. Inside it mounts three omnidirectional wheels of diameter length 120 mm The engines are DC brushless motors *Maxon 220251*, which can be controlled using motor control boards (10 Amp, 5 V - 30 V DC Motor Driver). The input voltage required for this type of base is 24 V, for this we used two 12 V lead batteries.

Figure 3.1: Large wheeled base

3.1.3. Robots

Below we present the list and a brief description of the robots used in the Physical Metaverse project.

Hook

Hook was the first physical avatar prototype made for this project [Figure 3.2]. It could move freely on the ground using three omnidirectional wheels (three DOFs). The base used in this case is the smaller one. This was chosen because of the height and the limited movements the robot can perform.
The upper module mounts a structure with three degrees of freedom. Each degree of freedom is associated with a servo motor. Each engine can be controlled individually and independently of the others; there is no high-level management.
In this case, the structure resembles a hook. One motor allows the rotation of the whole arm, while the two upper motors control the vertical bending of the different joints.

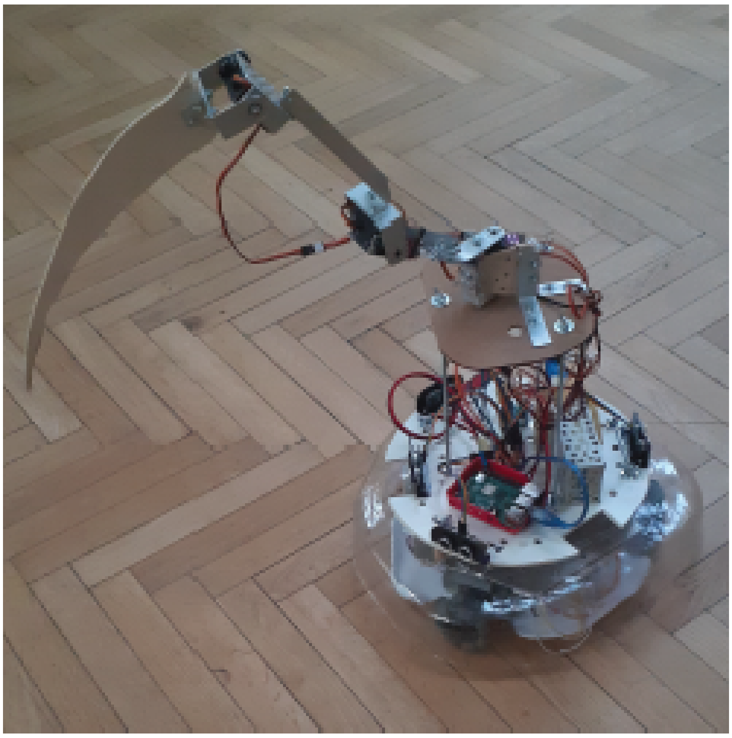


Figure 3.2: Hook robot

Seed

Seed is an example of a robot adapted to be included in this project [Figure 3.3]. The compact wheeled base was also used for this robot due to the small size and stable balance

of the structure.
The expressive module of the robot is technically more intricate than its predecessor. The structure is intended to recall the plant featured in the film *The Little Shop of Horrors*. This consists of four petals, a sphere with an LED inside, a fur interior, and a screen to show an eye. The petals are simultaneously controlled by a single degree of freedom. The mechanical structure is made in such a way as to translate the rotation of the servomotor shaft into a vertical movement of the petals. To make this movement possible, the petals are made in mixed papier-mâché.
The interior has been designed to be as interactive as possible: the light and the eye have been inserted to entice and make users understand the emotions expressed by the robot. The interior is covered in a soft material that invites touch. Beneath this material is a thermal sensor that can detect when a user is stroking the robot's head.
To mask the mechanical structure, a cover with fake ivy leaves was inserted, designed to recall the style of the character that inspired it.

Figure 3.3: Seed robot

Blackwing

The *Blackwing* robot was not initially intended for this project, but it was modified to suit its purpose [Figure 3.4].
Having a low weight and a tall but stable structure, it was possible to use the smaller wheeled base.
The upper module has two degrees of freedom, one that allows for forward-backward tilting of the structure and one degree of freedom that controls the opening and closing of two rods simultaneously.
The rods are fixed to a fabric sheet so that when the rods are fully open, the sheet is completely extended. This movement wants to remember a wing. The different amplitudes and speeds of the opening and closing movements make the robot capable of expressing a wide range of emotions in terms of type and intensity.
These two degrees of freedom are controlled at a low level, therefore autonomously and independently.

Figure 3.4: Blackwing robot

Scarecrow

This robot is the simplest made. It has allowed us to study interaction and movement without using many degrees of freedom [Figure 3.5].
The upper module of the robot consists solely of a static structure without any control systems or servomotors. Two wooden rods, one long and one short, were conjoined in a cross-shaped configuration and draped with a thin, partially translucent fabric. The cloth

was positioned and fixed to replicate the human structure.
The wheeled base used is the smallest one, given the minimum weight of the robot and its stability.
This structure, although not very complex, was appreciated for the effect of the gestures of the cloth following the robot's movement in space.

Figure 3.5: Scarecrow robot

Sonoma

Sonoma was designed to introduce a taller and more complex structure to this project [Figure 3.6]. Given the instability, height, and weight of this robot it was necessary to use the large wheeled base.
The upper structure is similar to that of the first Hook prototype. It consists of three degrees of freedom and three wooden rods connected by two joints. At the base of this arm is a servomotor that allows the arm to rotate. Given the size and weight of the structure, it was necessary to use a more powerful servomotor (torque 25 kg) to allow movement and avoid breaking the motor itself.
The other two servo motors were positioned on the last joints of the arm, allowing it to bend vertically.

Figure 3.6: Sonoma robot

3.1.4. Experiments

The starting point provided by the implementation and performance of the robots presented was of great help in the design process of the robot subject of this thesis.
The conclusions drawn from the tests carried out had an immense impact on the decisions made regarding the structure and nature of the movements.
We mention two experiences in which external users interacted with the robots presented within the Physical Metaverse project.

Digital Week – 11/12th November 2022

We presented our project as part of the Milano Digital Week [35] schedule held in November 2022. The demonstration regarding the Physical Metaverse project took place in a room provided by Politecnico di Milano.
The organization of the space was as follows. We divided the environment into two rooms, trying to make them as independent as possible. The two spaces created were visually independent: a person in one room could not see what was happening in the other one. The accesses were separate, and the public could only see one of the two rooms at a time. The experiences were divided into control and interaction, and we assigned a room to each.
The *control* experience involved one user at a time and was implemented as described in

the introduction to the project. The user was provided with a virtual reality viewer and the necessary controls to move the different degrees of freedom of the robot. During the experience, the user's goal was to interact and juggle within the virtual world, trying to turn on a light inside it.
The *interaction* experience was about actually interacting with the robot. In this room, one or more people were present with the robot. Their task was to interact and understand what the robot tells them to do and its moods. The only robot used in this experiment was *Seed*.
The two experiences were linked, but without the users knowing it. Whoever was using the headset was controlling the robot's degrees of freedom. Those who interacted with Seed changed the virtual environment seen by the viewer. The aim of the person handling the robot's controls, unbeknownst to him, was to make it clear to the interacting person to stroke the robot's head and stroke it. This allowed you to turn on the light in the virtual world.
At the end of the experiments, we draw helpful considerations on both experiences. Here are only illustrated those strictly related to the interaction with the robot.

- **Attention**
  The challenge in many interactions was to maintain the user's interest. The person will leave if the actions of the robot are not understood. This concept can be schematized with the term *Engagement*. Engagement is a process that occurs during an interaction and is used as a metric to determine its quality.
  There are several techniques to improve the level of engagement. One way would be to insert surprising movements during the interaction. The interaction can become boring and repetitive if a machine always performs the same movements.
  A useful consideration to make the interaction more stimulating is the a priori decision about the robot's character. This decision might seem limiting, but in reality, it allows to range within all the nuances of that character. It permits us not to generalize too much and to emphasize conflicting emotions. For example, if the robot is thought of as having a *calm* character and then a movement or outburst of *anger* is introduced, the span between these two movements will be very high. This span will capture the curiosity of the person interacting with the device.
  A last observation concerns the possibility of providing the robot with knowledge of the environment in which it is located. This would enable it to focus immediately on the relevant elements and leave out the secondary ones.

- **Physical Interaction**
  People's attention during the experience was not focused only on the most obvious

point of attention, as we expected. In reality, their interaction concerned the whole body of the robot.
It is important to detect the presence of an interaction in several points of the robot's body. This interaction can be physical, visual, or approaching the person.

- **Mistrust**
  The people involved in the experiment were not all encouraged to touch the structure. Many users, for fear of damaging the robot or distrust, did not interact. This requires managing distance and enticing people to approach and physically interact with the robot.

- **Language and listening**
  Users frequently asked about the robot's ability to emit and perceive sounds; even knowing they couldn't be heard, some people tried to talk to the robot.
  Given the nature of this project, linguistic and visual interaction is not to be considered because we want to succeed in creating a relationship starting only from movement. But this request underlines how even a simple sound could be relevant and used as a guideline in a relationship and exchange of information.

Workshop: My ROBOT Body – April 2023

My (ROBOT) body [43] was an intensive one-day workshop exploring technological innovation issues in artistic research for dance and theatre. The activities aimed to allow participating dancers, performers, and puppeteers to experiment with new ways of bodily expression about robots.
The activity occurred in a theatrical rehearsal space provided by the PimOff Theatre. The robots present were *Seed*, *Blackwing*, *Scarecrow*, and *Sonoma*.
Utilizing wearable sensors, the participants could manipulate the robots' movements to establish a reciprocal effect. The sensors available were of three types: accelerometers, sonars, and microphones. Each sensor could be attached to the body thanks to a 3D-printed plastic structure and straps.
The workshop opened with a warm-up session involving only the participants, without including the robots. The objective was to enter into a relationship with the movements of one's body, understanding what gestures were necessary to represent a precise emotion or state of mind.
Robots were introduced later. Each participant was asked how many and which sensors they would like to wear and where on their body. Furthermore, everyone could choose the robot to control, individually or in collaboration.
Once the connection between the robot and the individual was created, the latter was left

free to experiment with the movements of his own body to discover how the robot would respond, with which joints, and what sensation it generated.
The results of the day's testing showed the potential for a successful human-robot interface. In this exchange, one person's movements are reflected and remapped onto the robot's degrees of freedom. At the end of the workshop, each artist succeeded in constructing a short performance involving one or more robots. The performances were all meaningful and appreciated.
We drew several conclusions from this experience.

- The first noteworthy one concerns the structure of the robots. We found that the device did not need to perform articulated and complex movements to attract attention. Scarecrow was a widely favored robot due to its user-friendly control and the illusion of animation it created with its plastic top layer. This robot generated many feelings in the participants, generally related to the sense of the unknown.

- We noticed that the extent of the robot's movements is also relevant. Not only do they need to be precise and linear, but they also need to cover a wide arc so that the audience can observe them accurately. The same principle is applied in theatre and dance. The more a person performs extensive and confident gestures, the more meaningful the choreography becomes. This is also applicable in the process of making an emotion understood.

3.2. Considerations and possible improvements

The experiences made before the development of this dissertation project helped define the requirements and discard possible implementations that were unnecessary or inconsistent for the purpose to be achieved.
The goal of realizing a fully controlled and expressive robot consists of many aspects to be considered. In this section, we would like to mention the fundamental points that we have paid attention to throughout the construction and programming process.

3.2.1. Joint attention

During the Digital Week experience, the usual behavior of the participants was to become distracted and no longer consider the robot. This issue may be resolved by elevating the mutual focus between the robot and the person.
Attention [12] is the ability to choose and focus only on relevant stimuli and respond to them. In the interaction between people, *shared or joint attention* [44] is defined as the

shared focus of two individuals on an object. It can be achieved when one person draws the other's attention to an element of the surroundings.
Two internal roles are defined:

- The initiator of joint attention
  One who draws attention to an object.
- The responder to the request for joint attention
  one who notices the request of the interlocutor and shifts his focus voluntarily.

There are three different levels of shared attention:

1. Triadic joint attention
   This is the highest form of shared attention and involves two people looking at an object together, shifting their gaze only to look at each other.
2. Dyadic joint attention
   It is a conversation-like behavior in which individuals engage in. It is an exchange of words, generic sounds, and facial expressions.
3. Shared gaze
   This is the lowest form of joint attention. It specifies when two individuals are just looking at an object.

In human-robot interaction, and specifically for this thesis, we focused on the possibility of capturing the interlocutor's attention even in its lowest form, the gaze.
To achieve this, we have introduced techniques first used in social-behavioural theory. The primitive methods for directing a person's gaze are to look at him and follow his gaze a priori, then redirect it and provide explicit directional cues, such as pointing at an object using an end-effector.
Another aspect of efficient shared attention concerns the intention of the movements of the initiator. Intention is defined as a person's way of making it clear to others that they have a goal.
Intention can be regarded as the confidence of gestures. The robot must be able to move, point, or focus with the guarantee that it is explicit to the person from the outset what they are trying to do.
When designing the structure, we considered the need to keep the interlocutor's attention at all times by providing an end-effector that could be used to point or indicate a point recognizable to users as the robot's eye, thus conveying the idea of a gaze [27].

3.2.2. Expressive movements

Another aspect that emerged from the experiments regards how a robot does its gestures. How the robot performs a movement can change the dynamics of the interaction taking place.
Assessing a robot's proficiency necessitates an evaluation of not only the core elements of motion, for instance, accuracy, and velocity, but also how the user interprets them. The robot must express a state of mind so that the person understands what the goal of the interaction is.
A framework used for the expressive movement of a robot is defined by the *DESIRE* (or *SIRE* for short) parameter set, which means Description of Emotion through Speed, Intensity, Regularity, and Extent [34].

- Speed: concerns the speed of movement of the robot's limbs.
- Intensity: defines the nuances between smooth and abrupt movement. It modifies the values of acceleration and power.
- Regularity: defines the level of fluidity of movements, from smooth to rough.
- Extent: determines the amplitude of movements, how wide or contracted they should be in space.

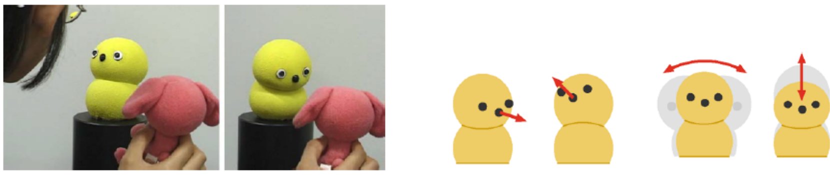
With these four levels of parameters, we can fully define a type of movement and make it as emotional as possible. Various combinations correspond to different emotions. An example of mapping can be:

- Happiness can be produced with med-high speed, med-low intensity, med-low regularity, and med-large extent.
- Sadness can be produced with low speed, medium intensity, med-high regularity, and medium extent.
- Anger can be produced with med-high speed, high intensity, med-low regularity, and a large extent.
- Fear can be produced with high speed, med-high intensity, medium-low regularity, and medium extent.

Focusing on the realization of movements defined by *regularity*, we studied different types of joints that could give as much movement fluidity as possible. Several existing robots have implemented mechanisms that could generate smooth and continuous gestures.

- Keepon

Keepon [32] is a small robot created for non-verbal interaction with children. This device has been specially kept simple to facilitate the conveyance of expressions to generate attention and emotion.
The structure resembles a 120 mm high snowman. The upper part has two eyes and a nose, which is a microphone. The lower part consists of small gimbals and wires controlled by four DC motors that allow the body to rotate and change position.
The material is soft and can be deformed by touch and the body's movements.
The body thus has four degrees of freedom, and these allow for different movements such as nodding (tilting forward and back), turning (panning left and right), rocking (leaning side-to-side), and bobbing (compressing vertically) [Figure 3.7b]. With these elementary gestures, both attentive and emotional actions can be constructed. With these two actions, *Keepon* can express what it perceives and how it evaluates the target [Figure 3.7a].



(a) Joint attention

(b) Illustration of Keepon's possible movements

Figure 3.7: Examples of Keepon movements

- TOFU

TOFU [70] is a social robot designed to replicate and mimic the expressive abilities of animated characters. The *squash and stretch* principle defined in the twelve basic principles of animation [Section 2.1.3] was used in this project.
The structure was created to maximize the expressiveness of the robot, keeping the number of actuators present as low as possible. Its body was designed to be as resistant to interactions as possible.
This robot consists of four degrees of freedom. Three actuators in the base allow the robot to lean forward, backward, right, or left. The fourth actuator is located upwards and allows the head to turn independently of the body [Figure 3.8].

Figure 3.8: Example of tofu's movements

- EMYS
  EMYS (EMotive headY System) [23] is a robotic head built for the *EU FP7 LIREC* project. Its purpose is to carry out research in the field of human-robot interaction. The head structure consists of three discs on which two eyes with movable eyelids are mounted, all placed on a neck that is also movable [Figure 3.9]. After the experiments, the tongue and lips were additionally implemented.
  The structure has a total of eleven degrees of freedom. Three in the neck, two for the eyes, four for the eyelids, and two for the upper and lower discs.
  The main moving elements of EMYS are its upper and lower disks. They are supposed to imitate the human raising eyebrows and dropping jaw, respectively.
  The eyelids can be opened and shut, and in conjunction with the eyes, they can traverse horizontally to heighten the expression conveyed. For example, to express sorrow or sadness, the eyes are turned outwards, while to express anger, they are frowning and turned inwards.
  The neck is designed to allow fluid movement of the head. The motors are positioned to allow a circular gesture of the entire structure above.
  During the experimental phase, Action Units (elementary movements of a single facial muscle) were defined, each associated with the movement of one or more joints.

Figure 3.9: EMYS head configurations

Given the description of the robots presented and the theory based on the knowledge of theatre and animation, we can conclude that a movement is as smooth as it is circular. The joint does not describe a straight trajectory, but a circular one.

3.2.3. Robot appearance

During the Digital Week experience and the workshop, we noticed how important the robot's appearance was in the interaction.
By the term *appearance* we mean not only the structure itself but also the materials used to make it.
In the context of Digital Week, where physical interaction with the robot was recognized by the thermal sensor placed on Seed's head, the materials used played a key role. People interacting with the robot were enticed to touch it in the exact spot by a piece of soft fabric placed correctly.
The aesthetic appearance of a robot can vary the effectiveness of the final interaction with a user. The covering of a part of the structure must be designed in such a way as to highlight its movements if necessary or make it inviting to scowl, touch, or even make it disappear into the background if not relevant to the interaction.
In general, the aesthetics of a robot must be thought through, taking into account the users with whom it will interact, the movements that the robot will have to make, and

the various points of the structure to highlight or cover if necessary.
Design is significant if you want to give users an initial bias to the robot's character. For example, using dark colors or angular formulas may give the idea of an evil or grumpy character. In the case of *Keepon* and *TOFU*, their aesthetics are reminiscent of soft toys designed to entice children to interact and play with them.

4 | Project Implementation

The fundamental purpose of the *Physical Metaverse* project is best expressed by the concept of *physical avatar embodiment*. This definition suggests the development of a complex framework enabling a person to embody a body distinct from their own without exiting the realm of reality.
The project's culminating outcome is to provide the person with a feeling of being inside another body. This avatar should be completely different from the user's body, but it has to allow interaction with the outside world.
With this objective in mind, we have defined several constraints that the structure to be realized must satisfy:

- The robot should have any shape. It will not have to reflect human features. This will allow us to explore the ways in which the operator of the avatar and the robot itself interact with their environment. The perception of the user controlling the robot will certainly be different. The aim is, therefore, not to replicate human sensibility, but to make the experience as immersive and new as possible.
- Avatars are physical systems that can exchange signals with the environment around them. The robot should include components that enable it to perceive the actions of those around it or even react to events like matching obstacles.
- The structure must be articulated in such a way that the actions of the controller can be mapped to the external environment. The objective is to enable users to understand that the robot conveys an action, sentiment, or message.
- This project makes explicit the choice to have a fully controlled robot. The robot should not have predetermined configurations, but the control of movements should be left to the subject impersonating the avatar.

In this section, we illustrate the process of building the robot subject of this thesis, from the prototyping phase to the final implementation. The first sections cover the preliminary steps and include the observations and corrections. We will then define the final realized structure component by component to argue each structural choice.

At the end of the chapter, we will discuss how the programming of limb movements was handled, the testing process conducted, and the subsequent modifications made.

4.1. Preliminary design

The first drawing of the structure attempts to highlight the first constraint related to the proposed framework. The intention was to design a versatile robot that could adjust according to the stimuli it receives.

> We were interested in testing our system with an avatar that could be as generic as possible, especially far from the human shape, but also without any explicit, clear-cut reference with any specific creature of character [21].

With this in mind, we thought of starting with a shape that is as generic and flat as possible. This structure had to be able to adapt to express a range of emotions, contingent upon both outside and user-generated signals linked to the robot's directives.
The avatar will thus be completely customizable by the person controlling it. In this way, it will be possible to study how the robot behaves and acts depending on the command it receives. Users will be free to express themselves, and their personality will be mapped onto the controlled avatar.

4.1.1. Emotion mapping

We can refer to the animation theory to represent a state of mind or an emotion. Considering the specific case of the animated character *Morph*© from the film *Treasure Island*©, it can be seen that he does not have a defined form.
Morph© expresses emotion by changing the positions of his body [Figure 4.1].

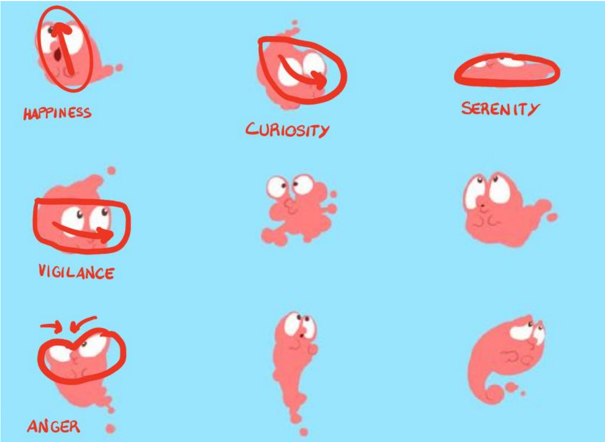


Figure 4.1: Example of Morph's movements

4.1.2. Robot description

The proposed robot is made up of two modules.
The first concerns the smaller wheeled base already used for the robots presented in the previous chapter. This will allow the robot to move freely in space and interact openly without having to move.
The second module consists of a panel made of a rigid, but lightweight material. A semi-transparent sheet has been be placed on top to mask the entire structure.
The plywood panel has been divided into two movable parts, and three pistons have been placed on each of these parts [Figure 4.2]. The idea behind the design of this module is to move the sheet to make it take different shapes according to the various inputs received.

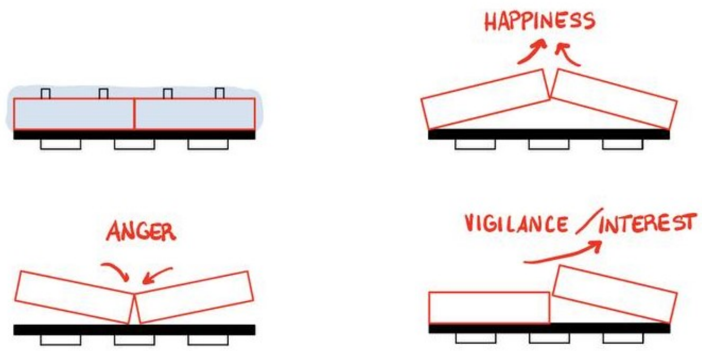


Figure 4.2: First design of the robot structure

Finally, in the upper module, we thought of adding colored lights. The aim was to make the emotion that the robot is trying to convey even more explicit using Plutchik's model [47] of the wheel of emotions [Figure 4.3]. In this model, eight primary emotions are defined: joy, trust, fear, surprise, sadness, expectation, anger, and disgust. Each primary emotion has an opposite pole and is based on the physiological reaction each creates in animals. Emotions not associated with a color represent possible combinations of primary emotions. As you move from the outside of the wheel to the center, the intensity of the emotion increases.

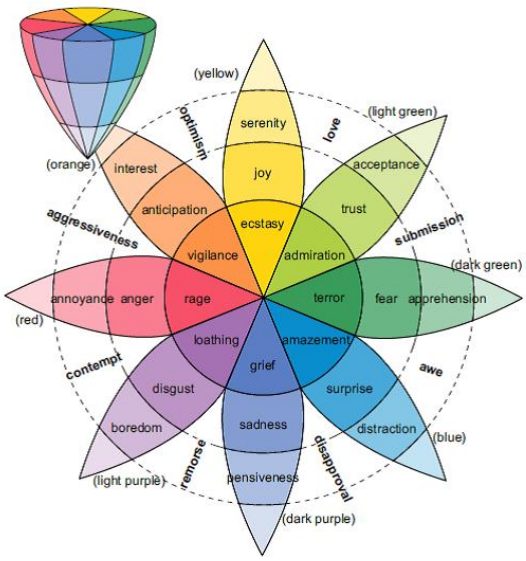


Figure 4.3: Illustration of Plutchik's model wheel of emotions

4.1.3. Problems and considerations

In the following, we illustrate the problems encountered in the design of this prototype:

- The first problem was the complexity of movement. The potential for the plywood base to shift in tandem with the pistons could lead to an imbalance in the structure, potentially causing a blockage. The conclusion was to immobilize the substructure and only move the pistons.
- The structure designed in this way will only work on the base. As a result, the complete movement will not be perceptible up close. It will be necessary to work on the height and exaggeration of the gestures.
- Using colors would make the robot too explicit in communicating. The aim is to create a model that conveys emotion with movements alone. One possibility could be to add fixed white LEDs so that the cloth disperses the light and highlights a specific point of the structure.

4.2. Prototypes

Based on the considerations that emerged during the realization of the first drawings, we modified the structure to improve it and make it suitable for our purpose.
The basic idea remains consistent with what was defined in the previous section. We want to create a robot whose form is mutable and expressive. The cover was also maintained

in the prototypes. Mechanisms such as pistons, telescopic towers, springs, or levers were used to achieve the natural and fluid movement of the cloth. Fluidity could be generated by ball joints or compressed air.

The elasticity of movement is a primary characteristic of Soft Robots, from which we have taken inspiration. This flexibility is given by the soft materials used that abstract biological muscles, tissues, and bone. Another feature of study concerning these devices is the management of the speed and acceleration of movements. As illustrated in the principles of animation, gestures should never be linear, nor at a constant velocity. The time difference in acting makes the character realistic.

One change that was made was the focus of the movements. We focused on a specific point of the body using an end-effector rather than the whole structure. We want to follow the pattern used in the performing arts (head, intention, and attention). This point must capture people's attention and make them understand the direction of movement. The light proposed in the first design is only integrated into the end-effector so that when it moves under the curtain, the gestures are emphasized.

Two types of movement are therefore identified:

- Directional, which allows the robot to express itself and interact.
- Biological, light but continuous movement that gives the illusion of vitality to the structure.

We considered adding fixed points on the robot's body to avoid confusion in the different types of actions and simplify the directionality of gestures.

The idea was taken from the features of ghosts in cartoons. The design is similar to a lamp on which a light sheet is placed.

We defined the movements of this structure by drawing inspiration from images taken from theatre and film culture. We identified different gestures for eleven emotions (astonishment, fear, happiness, regret, consent, disappointment, superiority, rejection, request, anger, curiosity) and drew a *hit and run* pattern for each of the perceived emotions [Figure 4.4].

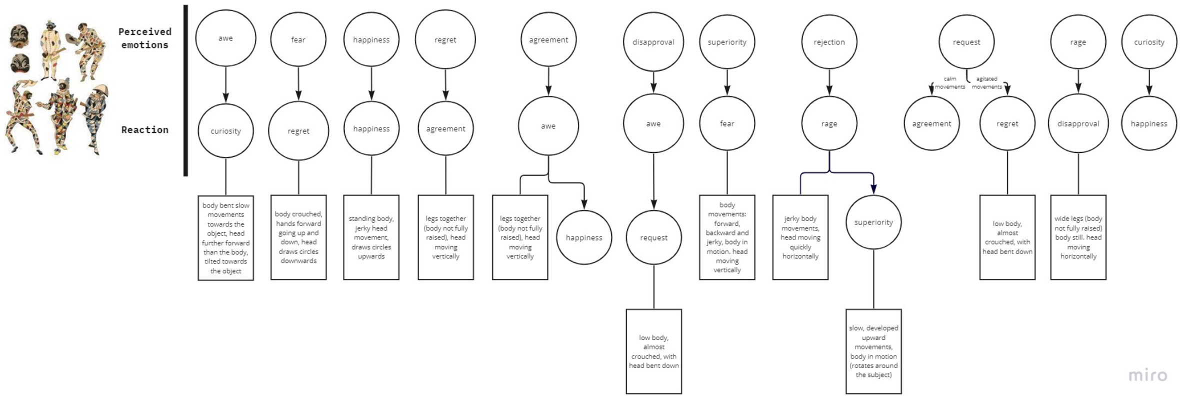


Figure 4.4: 'Hit and run' schema of perceived emotions

Attached, we have included a moodboard [Figure 4.5] to draw inferences from all these deliberations and to have a tangible illustration of the arrangement and the kinds of movements to be executed.

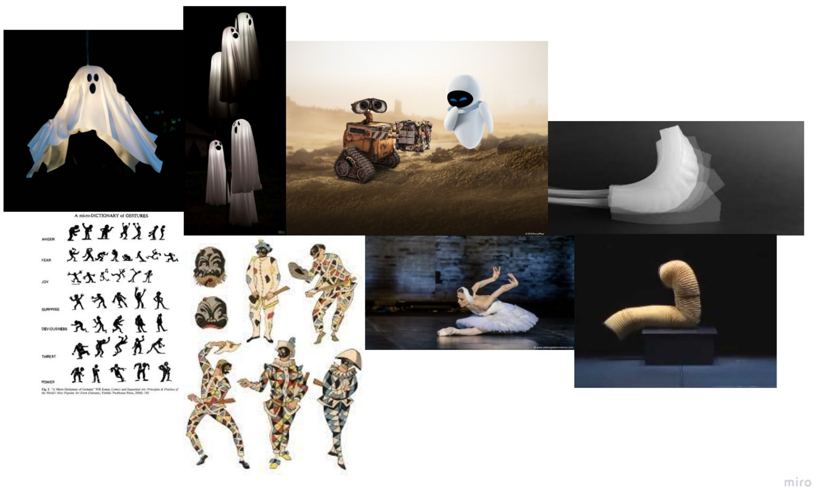


Figure 4.5: Project moodboard

4.2.1. Test: End-effector movements

This test aimed to check the visual effect of the structure as designed. We wanted to check the amplitude of the realizable movements, the material's elasticity, and the light effect placed on the chosen end-effector.
In particular, we wanted to test:

- The elasticity and tightness of the material covering the internal components.

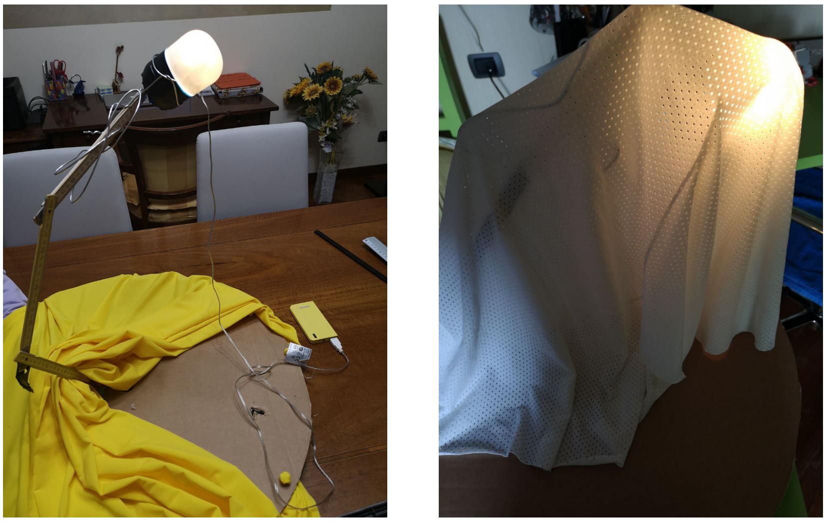
- The shape assumed by the structure following more or less rapid manipulation and changes in movement.

To carry out this experiment, we made an initial set-up. We cut a circular cardboard base with a central hole. We attached a lycra cloth to the edge, leaving it soft so there was room for movement. In the central hole, we placed a rod with a white light at the end [Figure 4.6a].

We realized the biological movements by moving a smaller rod in the lower part of the structure to which a sponge was attached. The position was specifically chosen to represent the effect of breathing as if it were a ribcage.

We manually rotated the mechanisms in different positions to check all possible critical points that could occur once the final mechanical structure was made. Following this experiment, we drew some conclusions:

- The end-effector to which we attached the light was heavy. This condition could be problematic for weight management at the end of an arm operated by servo motors for prototype use.
- The multi-jointed arm placed under the curtain appears to have a very angular shape [Figure 4.6b]. Shims could be used to chamfer the corners.
- Sponge appears to have a good effect as a shim. It is a light material but can move the cloth in a noticeable expansion.
- The cloth must be placed on the base, leaving plenty of slack. It must not be pulled, even when the mechanisms are switched off, as this could restrict vertical and horizontal movement.



(a) Inner arm (b) Light under a cloth

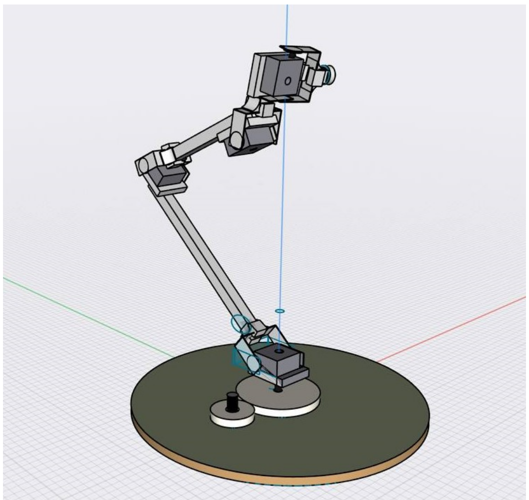
Figure 4.6: Examples of two test configurations

4.2.2. First mechanical prototype

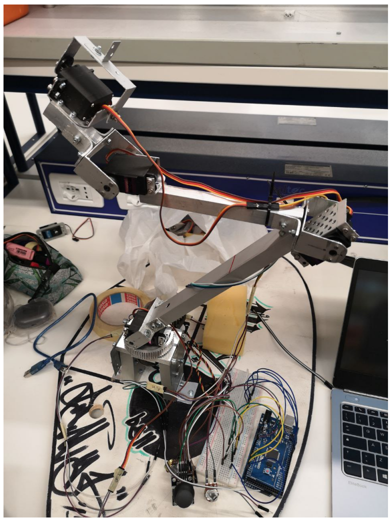
The structure of the avatar must be as expressive as possible, which is why we want the movement to be able to develop upwards and in width. The most complex component on a structural level is the arm that must support the point of attention and the end-effector. This mechanical arm will be the highest in the structure and have several degrees of freedom to guarantee fluid and articulated movements [Figure 4.7a].
We built an initial mechanical prototype to test the feasibility of an arm with different degrees of freedom [Figure 4.7b].
The total height of the final structure was estimated at around 70 cm. At maximum extension, the entire arm should cover 45 cm.
We divided the arm into five joints:

- Two at the base, defining a rotation and a vertical translation.
- Two intermediate ones for vertical translation only, dividing the arm into three joints.
- One on the end-effector which allows translation on the horizontal axis.

Each joint is independent and controlled by a dedicated servo motor. The servo motor model used is *Longruner MG996R Metal Gear (LKY62)* with a torsional moment of 12 kg/cm, powered at 6 V.
The entire structure was built with aluminum supports and a plywood base.



(a) 3D model of the arm



(b) Realization of the arm

Figure 4.7: Construction models of the arm

After the first test, we noticed that the strain on the motor at the base did not allow the complete extension of the whole arm linearly and smoothly. To avoid all the weight of the limb being on the baseline engine, we added a spring system to act as a counterbalance [Figure 4.8].

The result was satisfactory in terms of weight management. However, it added an unwanted rebound dynamic. Due to the necessity for exact arm movements, even very small elasticity rebounds could not be tolerated. In addition, the motors would have had to work harder to cope with the spring rebound after a sudden movement.

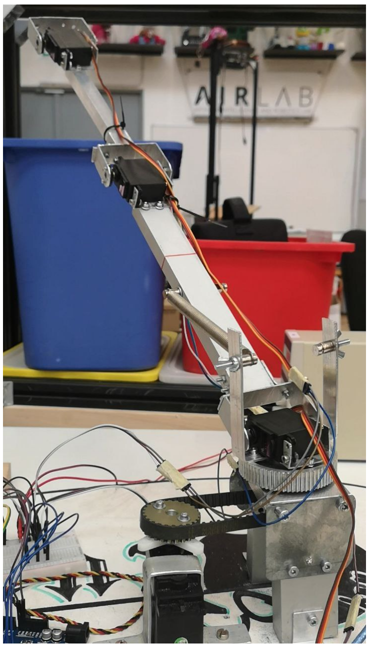
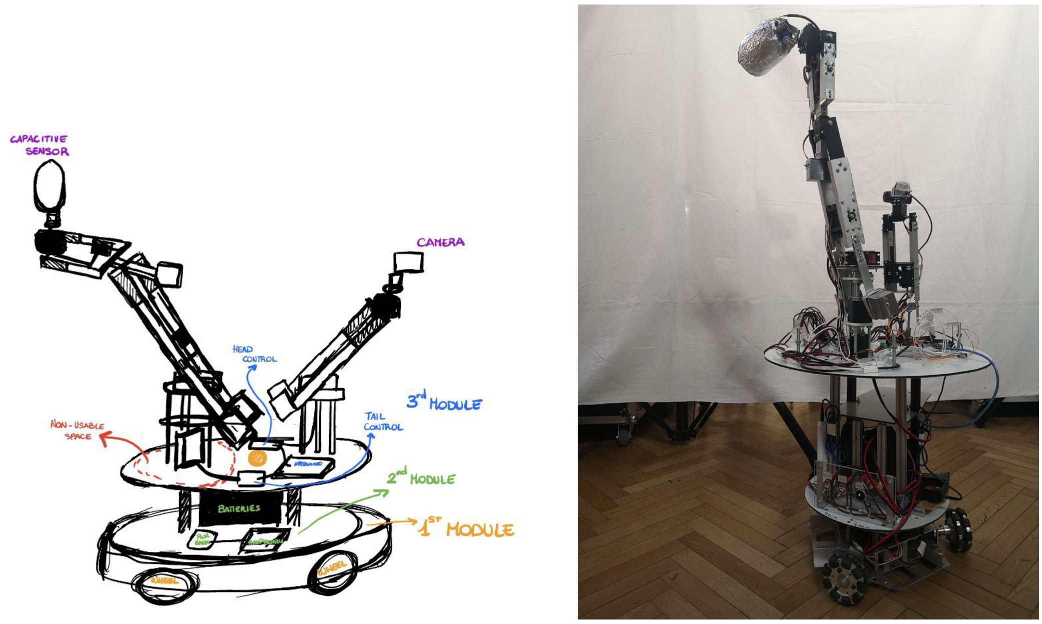


Figure 4.8: Realization of the spring system

4.3. Odile: Final structure

We started to design and then build the final structure of the robot based on what we had learned from the prototypes. We constructed a modular design by segmenting it into three distinct modules [Figures 4.9a and 4.9b].



(a) Sketch of Odile's structure (b) Realization of Odile's structure

Figure 4.9: Odile's construction models

In this section, we will go into each module in more detail, explaining the main mechanisms and how they were implemented.

4.3.1. First module: Wheeled base

The wheel module underwent several modifications during the development process of the robot [Figure 4.10].
Initially, we planned to use the smaller base that had already been completed and tested on other machines. After finishing the superior expressive structure, we opted to implement the larger wheelbase.
There are two main reasons for this choice:

- The robot's weight is too high to be supported by the smaller wheeled base. In all likelihood, we would have applied too much strain to the motors connected to the wheels and risked damaging them.
  In addition, the balance of the entire structure would also have failed. For example, following an abrupt braking maneuver, the robot could have become unbalanced and strained just one of the three motors, making all subsequent movements unfeasible.
- The velocity yielded by the minor base is not as high as the one we can obtain from the larger base. To create as prompt a reaction as possible, we wanted to manage

the movement in space in such a way as to have possibilities to play with speed and acceleration.

The used base was reworked to make it functional and applicable to Odile's structure, conforming to those already implemented for the other devices.
The wheels are omnidirectional with a diameter of 100 mm and have two rows of rollers. The motors used are *DC brushless Maxon 220251*. The support structure is made of aluminum.

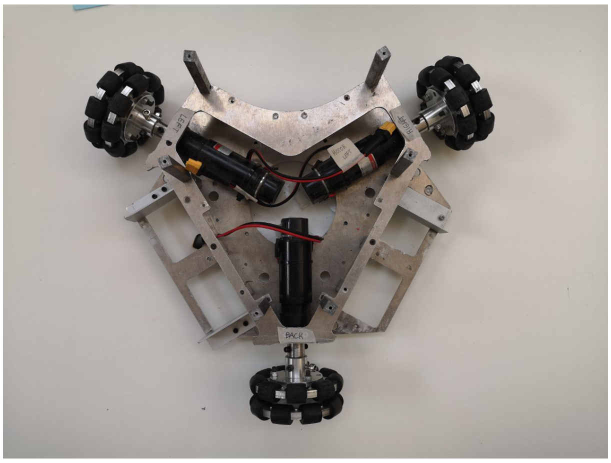
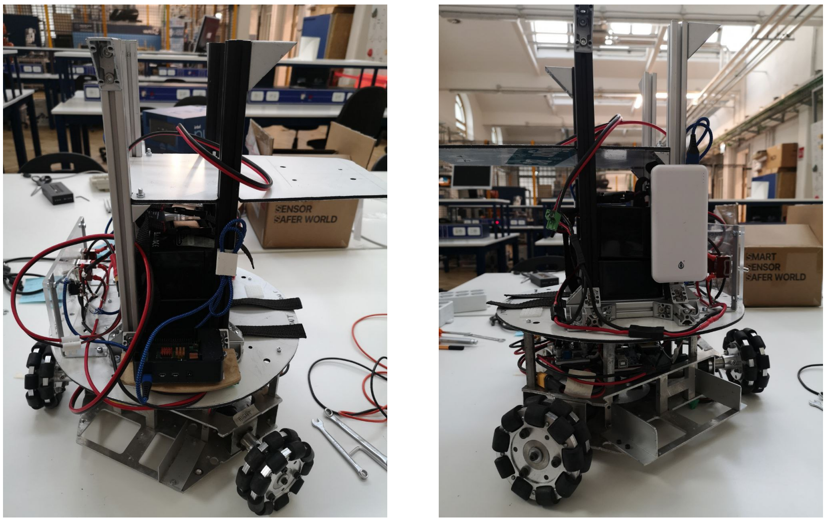


Figure 4.10: Wheelbase structure

4.3.2. Second module: Core

Odile's second module is dedicated to powering all the components, and it also houses the robot's central controller, namely Raspberry Pi, designed to be connected to the lower and upper modules. We have configured this type of control so that it can be extended to more modules.
The whole structure needs two batteries of 12 V each [Figure 4.11a]. We used two lead-acid batteries that can be found on common mopeds. Given the relatively high weight (5 kg), they were also used to balance the entire robot.
The core also contains the power supply for the Raspberry [Figure 4.11b]. This component requires a separate power supply. We used a rechargeable power bank with USB output. Within this section, we have added support for *LiDAR*. Not used within the scope of this thesis project, but prepared for future research.



(a) Lead-acid batteries and *LiDAR* support

(b) Power bank

Figure 4.11: Core structure

4.3.3. Third module: Expressive structure

This module contains all the truly expressive and interactive parts of Odile. The expressive part consists of two mechanical arms, one more articulated than the other. We used aluminum and 3D-printed plastic as materials.

Both components are placed on a circular plate with a diameter of 520 mm and at a distance of 180 mm from each other.

The most complex arm in terms of degrees of freedom is 700 mm long at maximum extension. This represents the *tail* of the robot and the point of focus for the direction of movement. To render the idea of a realistic tail, we positioned the arm in the opposite direction to the movement of the wheeled base.

The smaller arm has a length of 400 mm at maximum extension. This represents the *head* of the robot and the gazer. The task of this arm will be to seek the eye contact of the person with whom the robot interacts and bring his attention towards the robot itself or an external point of interest. We positioned the arm in a direction that conforms to the forward movement of the wheeled base. The purpose was to give the idea of the eye and the directionality of the overall body movement.

The position of both arms is not perfectly centered about the robot axis but shifted forward to ensure the overall balance of the robot.

Starting from the preliminary ideas given by the prototypes, we arrived at different mechanical construction approaches that we tried to replicate for all joints of the structure to make it as uniform as possible. In particular, we made two changes to the structure of the mechanical arms:

- Regarding the motors positioned on the moving arm and not fixed to the base, we managed the transmission of the shift to the respective joint using a belt system. In this way, we lowered the position of the motors by shifting the weight towards the base and increasing the overall stability. The models of belts and pulleys we used are those provided as spare parts for 3D printers. We chose this model because of its small size.
- The expressiveness of the robot is provided by the movement of the head and tail end-effectors. In both cases, we paid attention to how to manage them and achieve a fluid gesture.

To achieve this, we studied the possible gestures of the human neck, which can make circular movements. We drew on the study carried out on the *EMYS robot* [40] [41] and its mechanics. The structure used by the manufacturers is defined as *Tilt-Pan-Tilt*.
In this pyramidal structure, the bottom two motors are joined to the upper motor at the extremities. The pyramid base handles tilting the head forward or backward (*tilt*), while the top engine handles the rotation (*pan*).
We did not have space for a pyramidal structure. This mechanism is applied to both end-effectors of the two arms. We have realized a similar arrangement by positioning the three motors vertically, as close to each other as possible, following the tilt-pan-tilt order. The first tilt is positioned close to the last joint on the arm. A belt system transmits the tilt angle to the pan motor. Finally, the pan is directly connected to the second tilt. The top motor is fitted with the end-effector of the joint.

Tail

The tail was the first to be finalized because of its mechanical complexity.
It consists of six degrees of freedom. In the following, we have illustrated the main characteristics and problems encountered for each one, starting with the base and ending with the end-effector.

1. **Base rotation**
   The initial idea from the prototypes we made led us to consider a full 360° rotation of the arm. The aim was to have as much range of movement as possible.
   Later, given the need to introduce the head joint, we limited the rotation to 180°. The motor used for this joint is *HS785HB sail winch servo*, which allows a maximum torque of 13.2 kg/cm.

One problem we encountered concerns the management of the weight directly on the motor shaft. We tried to manage the mechanics by moving the motor away from the center of rotation of the boom and transmitting the movement via a belt system [Figure 4.12].

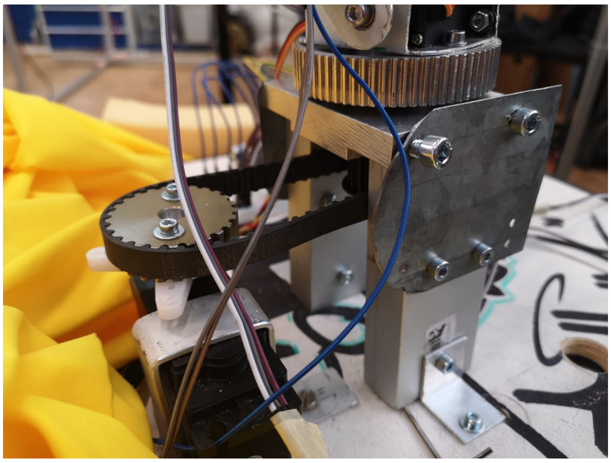


Figure 4.12: First rotation prototype

However, this mechanism did not provide good results for the type of movement we hoped for.
We implemented another type of mechanism called a *double bearing* [Figure 4.13]. This is a vertical structure in which the motor is placed on an axis concerning the rotation of the arm. The motor is connected to a shaft passing through two cushioned planes to support the weight on top. The end of the axis is connected directly to the component that is to rotate using thrust bearings that discharge its weight.
Thanks to these modifications, we have achieved a smooth and immediate movement of the drive.

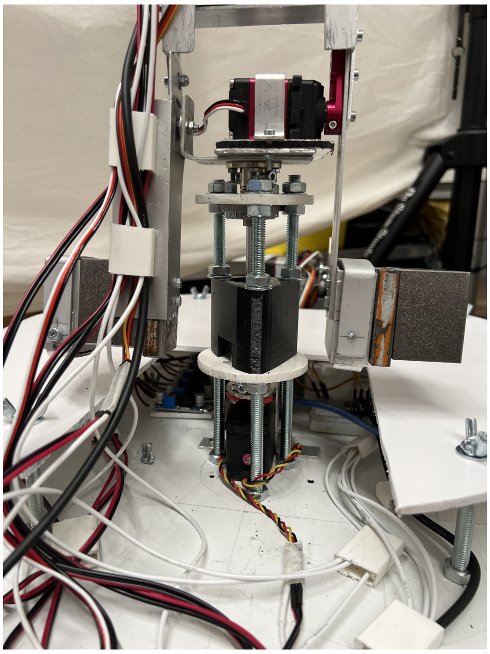


Figure 4.13: Final rotation mechanism

2. **Vertical base tilt**

   The realization of this joint was problematic because the weight that the engine has to support is very high.
   In the prototypes, the overall weight of the arm was not managed, which made the whole structure unstable.
   The improvements made can be summarised in three points:

   - We moved the motors towards the base, using belts to transmit their movement. This resulted in a favorable weight distribution and increased stability.
   - To distribute the overall weight influencing the motor, we built a horn structure with a bearing on the opposite side of the shaft.
   - Given the weight of the entire structure, which was greater than that manageable by one of the servo motors previously used, we changed the component. We used the *DS5160* motor. It provides a torque of 60 kg/cm but requires a higher power supply (8 V) than the other servomotors used.
   - After calculating the weight distribution and center of gravity, we added two counterweights (500 g each), one on each motor side [Figure 4.14]. We shifted the new center of gravity towards the motor in question, exploiting as much torque as possible.

Figure 4.14: Base tilt mechanism

3. **Intermediate joint tilt**
   We added a second degree of freedom in the middle part of the arm, similar to the vertical translation generated by the motor at the base.
   To ensure balanced force across the entire limb, we moved this joint motor to a lower position. Consequently, the transmission of the shaft movement was carried out using a belt [Figure 4.15].
   The transmission components consist of a belt and two pulleys. One is located at the motor shaft, and the other is positioned on the joint subject to the movement. We designed the mechanism at the motor to distribute the weight and avoid unstable movements. We fixed it horizontally on the aluminum structure. To secure the pulley to the motor, we designed an ad hoc component consisting of a flange at the top and a cross-shaped joint to be attached to the motor cap. The flange attaches a shaft to the aluminum structure via a single-bearing mechanism.
   At the end of the belt is another pulley. The difficulty of this mechanism lies in managing the free rotation of the arm along an axis. To realize this mechanism, we designed an interlocking component divided into two ends, one designed to hold the pulley and the other to hold a bearing. The axle and the arm move in solidarity with each other. The ends of the axle are attached via two bearings to a component designed to make the outer aluminum arm independent of the movement of the inner axle.

We encountered two problems for which structural modifications were necessary:

- The weight at the end of the second joint was too high to be supported by the motor model used. We applied the method used with the vertical traversing motor and added a counterweight (490 g) to the opposite end of the arm.
- After several tests, we realized that the motor moving the whole arm was under stress. The designed flange did not allow for stable support for the entire structure, making the motor subject to wear and non-smooth behavior. We changed the support mechanism and implemented a horizontal double-bearing structure so that the entire weight of the arm is unloaded onto two intermediate bearings without relying solely on the motor seal [Figure 4.16].

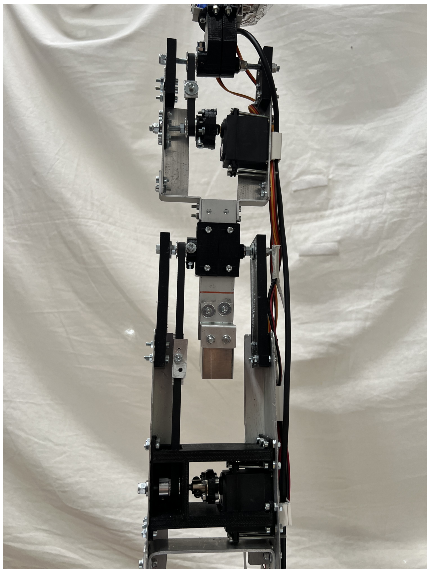
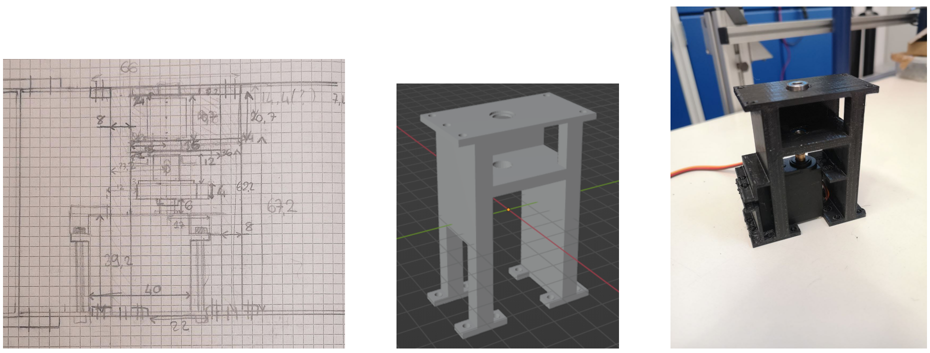


Figure 4.15: Neck tilt mechanism

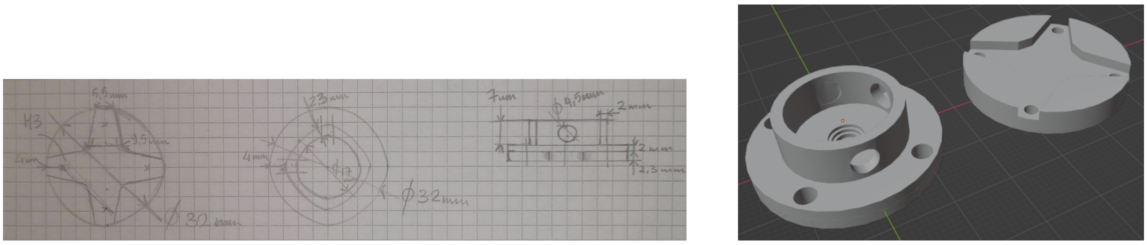


(a) Sketch (b) 3D model (c) Printed element

Figure 4.16: Horizontal double bearing mechanism

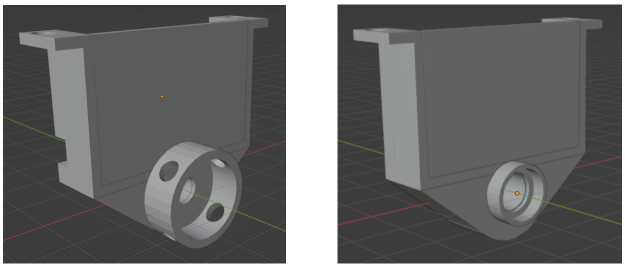
4. **Tilt-Pan-Tilt**
   At the tail end is the tilt-pan-tilt composite mechanism, designed to replicate the ergonomic movement of the neck and make the end-effector as representative as possible.
   As described earlier in this section, this mechanism consists of three motors placed in a vertical sequence [Figure 4.17].
   The first tilt motor is responsible for the vertical translation of the pair of servos positioned above. Transmission is via a belt, and the mechanism connecting the motor, the pulley, and the aluminum structure is a replica of the first version described for the intermediate joint [Figure 4.18].
   We have designed the connection between the end-effector's rotation motor and the translation axis driven by the transmission in a manner consistent with that illustrated for the previous joint. The only difference lies in keeping the movements as compact as possible to achieve a consistent tilt-pan-tilt structure. We decided to tie the motor and the vertical traversing axis directly [Figure 4.19].
   To minimize the arm weight in the end-effector area, we used a servo motor of reduced size and torque as the second tilt motor. Due to the low weight that this component has to bear, we used a small servomotor.

Figure 4.17: Tilt-Pan-Tilt mechanism



(a) Flange sketch (b) 3D model of the flange

Figure 4.18: Flange models of the low tilt motor



(a) Pulley support (b) Bearing support

Figure 4.19: 3D models of the pan motor support

5. **End-Effector**
   Odile's tail is intended to define the direction of movement. To make the interaction complete, it is necessary to receive stimuli from the external environment. To achieve this, we connected a capacitive sensor (Breakout with capacitive touch sensor *MPR121, Adafruit*) to the end-effector.
   When connected to a conductive surface, this sensor can detect touch. We covered the end-effector with tin foil, using it as a conductive material, and carried the signal from the surface to the sensor via an insulated cable. This provides a cleaner signal and avoids interference.

Head

The smaller arm implements Odile's head. It consists of four degrees of freedom. A smaller structure was deliberately chosen to avoid having two points of attention of movement. This arm is necessary to give completeness to the overall gesture of the robot.
Since this arm does not support rotation in place, the entire mechanism that regulates this movement was not realized. This had a side effect regarding the height of the point of origin of the arm movement. We risked losing the effectiveness of the gestures due to the

height difference between the tail and the head. To avoid placing the first motor directly on the module platform, we inserted a support to raise the point of origin of the vertical inclination.
In the following, we illustrate the levels of this arm by clarifying its characteristics.

1. **Vertical base tilt**
   The mechanism that adjusts the inclination of the entire boom has been designed in a mirror-image manner to the one designed for the tail [Figure 4.20]. The only difference is the type of motor and overall weight management.
   The motor used is less powerful than in the previous case. It is the *DS3225* model and has a torque of 25 kg/cm. Due to the simplified structure of this arm, there was no need for a more powerful servomotor or weight management using counterweights.

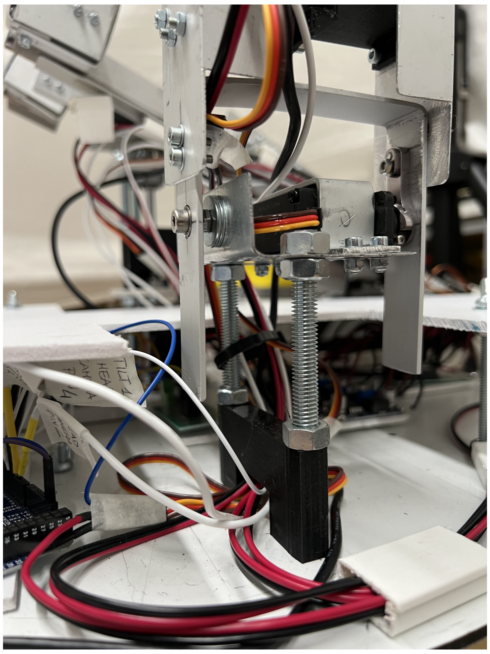


Figure 4.20: Vertical base tilt mechanism

2. **Tilt-Pan-Tilt**
   To achieve better performance, we have included the *tilt-pan-tilt* mechanism in this model [Figure 4.21].
   The way we deal with the first tilt motor has changed from before. We figured that to keep the engine from being shaky when it goes down, we'd have to create another double-bearing structure.

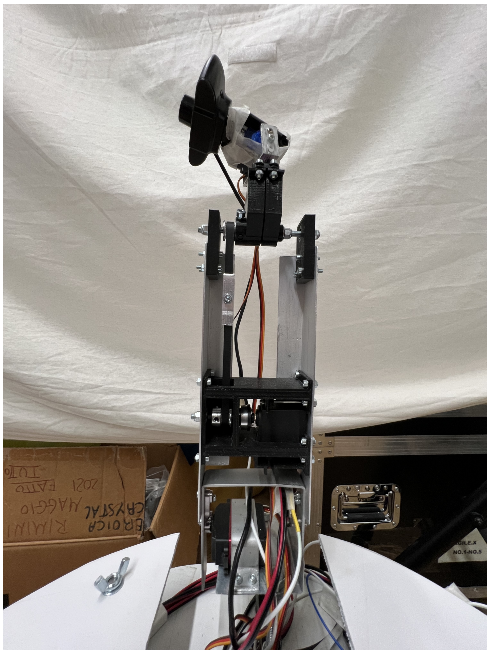


Figure 4.21: Tilt-Pan-Tilt mechanism

3. **End-Effector** To make the role of the end-effector's eye of this arm explicit, we connected a webcam to the end.
   The webcam allows the robot controller to get visual feedback on its surroundings. It can orient itself and interface with other people or things.
   The webcam is controlled directly by the Raspberry, which is connected via a USB cable.

4.4. Electronics and circuitry

In this section, we would like to illustrate all the control and circuitry components built to enable the correct operation of each module.

4.4.1. First module: Wheeled base

The components chosen and manufactured for Odile's first module follow the guidelines of the wheeled bases made for the robots presented in the previous chapter [Figure 4.22]. The elements on board are as follows:

- Arduino UNO.
- Step down (DC/DC converter, 3 V to 40 V input, 1.5 V to 35 V adjustable output).
- Driver for two DC motors with a supply voltage between 7 V and 35 V.

- Driver for a single DC motor with a supply voltage between 7 V and 35 V.

The input voltage to the module is 24 V. This is divided into three outputs: two for the motor boards and one for the Arduino. On the implemented circuit there is a common ground track for all components.
The pins on the drivers for controlling the motors are connected to the PWM pins on the Arduino board.

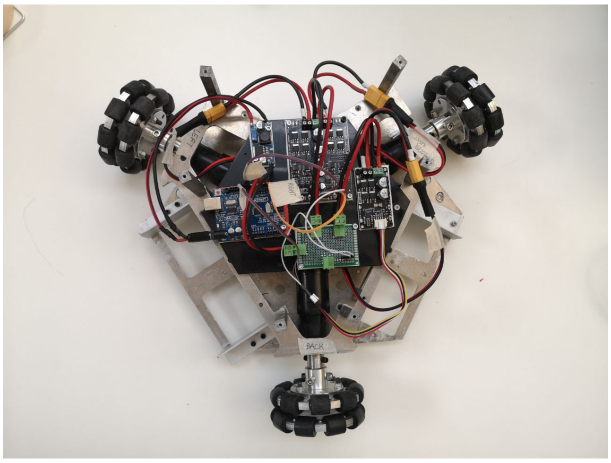


Figure 4.22: Wheelbase electronic components

4.4.2. Second module: Core

The 24 V lead battery power supply has two independent output lines, one for each module. We made three switches to supply power to the two modules and the Raspberry independently. This choice preserves the modular design idea and allows the different modules to be tested individually and conveniently [Figure 4.23].

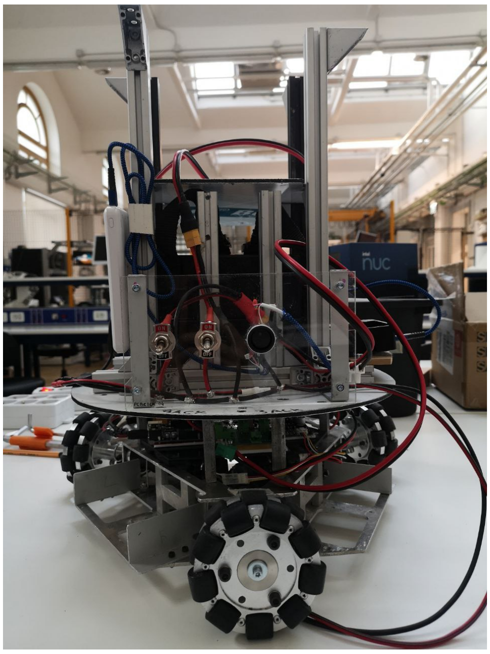


Figure 4.23: Power supply switches

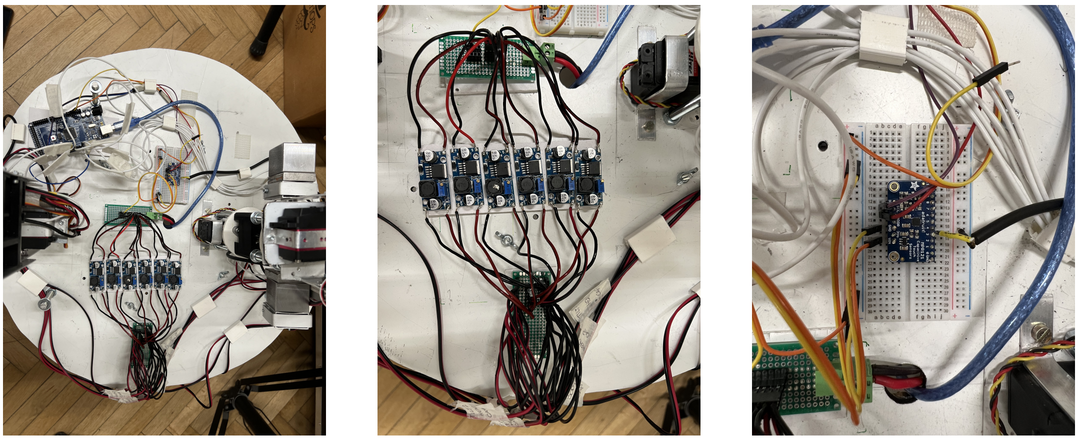
4.4.3. Third module: Expressive structure

The third module consists of servomotors or generic sensors controlled via Arduino [Figure 4.24a]. The elements in this module are:

- Arduino Mega.
- Six step-down (DC/DC converter, 3 V to 40 V input, 1.5 V to 35 V adjustable output).

The input voltage to the module is 24 V. This is directed to six different step-downs, which make it possible to limit the amplitude and make the input voltage applicable to the motors without damaging them [Figure 4.24b]. One step-down is entirely dedicated to the servo relating to the vertical translation at the base of the tail. This is because it requires an input voltage of 8 V, which does not conform to that of the other servo motors on the structure. The second step down is dedicated to the winch servo motor, which is required for rotation at the base of the tail (needs a supply voltage of 5 V).
Each of the remaining four step-downs is assigned to two motors: this is done to limit the components on board the robot and to avoid voltage drops or malfunctions.
The output voltage re-calibrated by the step-downs is divided between the motors thanks to a purpose-built circuit.
The capacitive sensor in this module is powered directly by the Arduino and connected to the common ground [Figure 4.24c].

A separate mention concerns the management of the connection cables between the motors and the data and power pins. During prototyping, we used the classic jumpers provided for Arduino. Due to the height of the arms and the configurations they can take, we extended the cables by connecting them in series with each other. These cables are not suitable for such large constructions, do not provide signal continuity, and we often experienced sudden voltage drops. We decided to remove all the extended cables and make individual cables to size to avoid discontinuities.



(a) General electronics on the third module

(b) Step-down circuit

(c) Capacitive sensor

Figure 4.24: Electronic components of Odile's third module

4.5. Programming and testing

Once the physical structure of Odile was completed, we moved to the implementation part of the movements and controls.
In this section, we illustrate the differences between the different implementations and discuss the motivations that led us to deepen or discard particular choices.
We introduce both the implemented movement configurations and the different types of controls used to test the robot's gestures.

4.5.1. Programming movements

Movement programming refers to the implementation part required to realize the different position combinations of the servo motors. For each configuration, the aim was to find a representative behavior of a mood or an emotion and, at the same time, to make it controllable from the outside.
We did not want to program the robot's movements by making it autonomous but rather

to simplify the control for the user by making Odile's many degrees of freedom more compact. The programming of the modules under discussion here was done using the *C++* language and the *Arduino IDE* software.

Wheeled base

The programming for the first module was taken directly from the Sonoma [Section 3.1.3] robot project, as the used motors are the same. However, we applied several modifications during testing. For example, we made the base slower to avoid unexpected behavior.
A relevant addition concerns the frequency management of the PWM signal given to the motors. By modifying this parameter, we corrected the sound generated by the DC motors by making the base's movements silent.

Single-motor control

This type of control was the simplest achieved. It involves controlling each motor individually, each with its limits of movement.
Although this method is simple to implement, it makes the control of the robot complex. The entire structure offers thirteen degrees of freedom, and controlling each motor separately would require the user to manage thirteen independent commands. This is not easily applicable in every context. We looked for other systems to make the number of controls as compact as possible.

Sigmoid and predefined sequences

We wanted to test the expressiveness of the end-effector joints by binding the three degrees of freedom together and constructing predefined movement sequences.
Our goal was to create an animation that followed one of the basic principles described by Disney animators, namely *Slow In and Slow Out* [52] [Section 2.1.3]. By slowing down the start and end of the overall movement, we could give the idea of a gesture expressing curiosity or surprise, depending on whether the action develops downwards or upwards.
We implemented a *sigmoidal movement pattern*, defining three intervals in which the motor would move at different speeds (slower, increasing speed, and finally slowing down).
The library we used to manage the speed variation of each motor involved is *VarSpeedServo* [56]. Thanks to the implemented functions, it is possible to define speeds for each action and complex motion sequences composed of any number of intervals.

Step vs. Sinusoidal function

During the first tests to check the functioning and expressiveness of the structure, we noticed that the difference between the moods was not always clear. We identified two opposite feelings, calm and agitation, and implemented them through movement configurations for the entire emotional structure.
The aim was to achieve a constant movement of the structure, according to the *Secondary Action* principle defined by the Disney animators [52] [Section 2.1.3]. We designed the gestures in question to be always present but without affecting the accuracy of the position controls of the degrees of freedom of the structure.
For the two defined states of mind, we programmed two different scenarios:

- Agitation
  To emphasize this emotion, we have used a step function. The position of the motors changes when the function changes state (down-up and up-down) and then remains constant until the subsequent state changes.
  The period and amplitude of the motors' motion were randomly generated in a range of values from 0 to a number arbitrarily chosen in real-time by the robot controller. This random generation allowed us to obtain a jerky behavior of the structure by highlighting its agitation and shaking.

- Calm
  We identified the mood related to calmness as generated by a sine function. As in the case of the step, we allowed the controller to choose the amplitude and frequency of the curve. The parameters were not randomly generated in a range, but we applied the values directly.
  Thanks to this function, we achieved a slower and more gradual bounce of movements, which allowed us to emphasize an emotion of calm and tranquillity.

We encountered some problems when implementing these controls:

- The movements related to the sine wave for high frequencies and low amplitudes were reminiscent of a step movement. Under these conditions, it was impossible to differentiate the two behaviors. We experimentally set up a threshold relative to both parameters so the controller would not overshoot in either direction.

- Including these configurations further complicated the controls by introducing three parameters. One value concerned the secondary motion mode selector (0: standard, 1: agitation, 2: calm). The remaining two values represented amplitude and frequency of movement.

Inverse Kinematics

Given the amount of controllable parameters, which is too high for one person, we explored different methods to tie the movements of the motors together as much as possible while maintaining expressiveness.

We started with Odile's tail because it is more articulated than the head. We translated the arm movements into the movements of the end-effector, shifting the focus to its position only. Using inverse kinematics, we implemented a model that, given the desired coordinates, would bring the end-effector to the correct position by autonomously articulating the arm.

We measured the attainable space around the robot and defined three reference axes *(x, y, and z)* with their domains. By then applying the mathematical formulae as described by theory, we were able to obtain the desired behavior.

The problem encountered concerns the expression of the obtained movements. Although Odile's tail has several degrees of freedom, it is still too simple and unarticulated to achieve the desired gestures and maintain its expressiveness. The arm assumed the necessary positions, but the joint articulation did not follow the predefined movement pattern.

Movement restricted to three DOF

As the inverse kinematics test was unsuccessful, we wanted to look for other methods to bind the control of the whole arm.

By studying the physiognomy and movement of the spine, we defined three basic gestures:

1. **Forward and backward**
   This movement is mainly related to the lowest joint position, starting from the base [Figure 4.25]. The overall sequence is divided into steps. Depending on the pose of the lower joint (r1 in Figure 4.25), the position of the high joint (r2) changes.
   To realize this configuration, we connected the movements of the vertical tilt motors to the base and the first tilt in the tilt-pan-tilt model. The angle given to the base servo motor is re-scaled to the range of values attainable by the second motor. This keeps the end-effector parallel to the floor and easy to control, depending on the tilt of the arm.

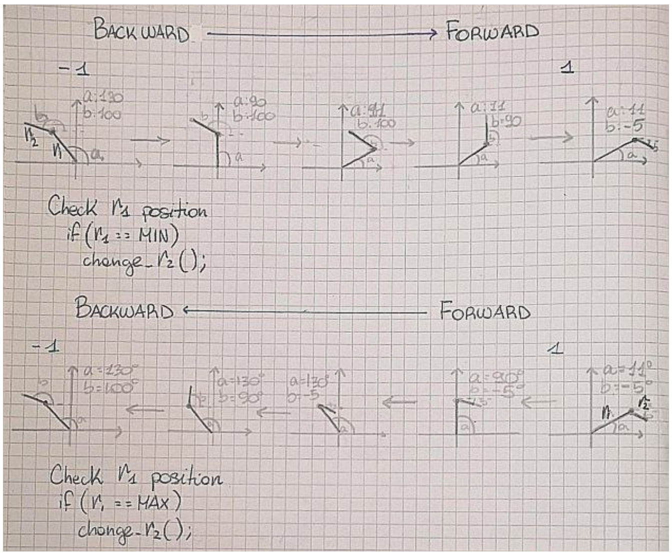


Figure 4.25: Sketch of backward and forward pattern

2. **High and Low**
   This sequence concerns the position of the high joint (r2) [Figure 4.26]. In this case, we have defined the overall movement mapping on r2 by making the r1 joint dependent.
   As in the previous case, we have linked the movement of two motors using a proportion of movement angles. We connected the second intermediate motor for the tilt along the vertical axis and the second tilt of the end-effector.

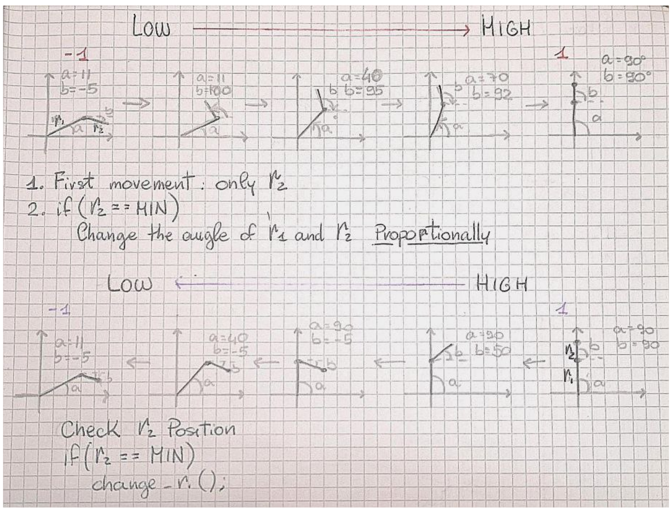


Figure 4.26: Sketch of high and low pattern

3. **Left and Right**
   This movement is the simplest because it is linked to the rotation of the base. To

make this rotation match the one of the end-effector, we connected the base motor to the pan at the end.

Through implementing these settings, the arm motions were more expressive and more understandable than those created by inverse kinematics. In addition, we halved the independent controls for the tail.
By applying this method to the head, we reduced the control of the entire robot to a total of nine degrees of freedom.

4.5.2. Control

During the tests made to check the movement of the joints, we tried different types of control and checked which one was the most manageable.

Potentiometers

Prototyping control did not require a large amount of components. We tested the function and tightness of the couplings using several potentiometers, checking the position motor by motor [Figure 4.27].
We read the value defined by a potentiometer and remapped this value to the assigned motor movement range.
This method helped us to define the movement intervals for each motor.

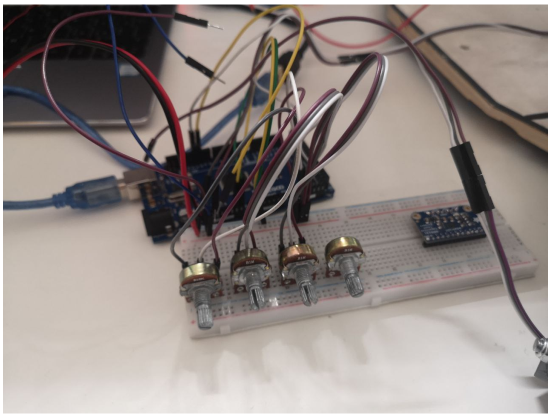


Figure 4.27: Board with potentiometers

Remote control

Bringing the discussion back to the *Physical Metaverse* project, we used a series of implemented controls for remote communication [10].
We read the control values from each control, inserted the value into a UDP message in

the format *[key: value]*, and sent it to the Raspberry Pi on board the robot.
Once the message was received, we processed the values and used Raspberry to redirect the commands to the correct module (Wheeled base or upper emotional structure).
We sent the commands to Arduino via serial communication in *[key: value]* format. Depending on the key received, Arduino selects the motor to be moved and applies an angle to it consistent with the received value.
This communication format was used for all the control systems tested:

- **ESP connected to sensors**
  This control method is the most appropriate for the general purpose of the project; however, due to the complexity of the structure, it was not possible to employ this control and achieve expressive robot behavior.

- **Joystick**
  With this controller, we managed to map the nine degrees of freedom set up for Odile's movement. However, some selected buttons were still inaccurate and required some effort.

- **VR and joysticks**
  The virtual reality visor and its associated joysticks offered us usable controls and much precision. We used *Oculus Quest 2* controllers.
  We mapped Odile's head movement using two directions of the accelerometer on the VR visor. The joystick in the left hand controlled the three degrees of freedom of the wheeled base (via joypad and gripper). The joystick in the right hand used both the gripper and the joypad to control the remaining motors of the upper third module.
  This type of control was the most effective and linear due to the impulsiveness of the gripper and the precision of value detection provided by the joypads.

4.6. Coverage

The primary concept highlighted by the prototypes was to use a cover that would conceal the two arms and highlight only the landmarks. During the structural development, we encountered several problems with the use of a cover:

- the camera has to be uncovered to ensure a clear view of the surroundings.
- The cover provides additional traction that has to be supported by the motors.

These problems led us to cover only the mechanical part, leaving the end-effectors uncovered and free of weight [Figure 4.28].

Figure 4.28: Odile covered with a white fabric

4.7. Modifications made in the test phase

In this section, we would like to present the additional considerations made in preparation for the final phase of the experiments. After testing the entire structure using the viewer and its joysticks, we noticed two types of problems:

- Some motors were misaligned. These did not cover the correct angle range for meaningful movement. We adjusted the magnitude of the angularity parameters to ensure a broad and regular motion for every setup.
- The position of the two arms about the base was unfavorable for control. The head points in the tail's opposite direction, which does not allow the controller to see its movement and consequently affect control.
  We turned the motor relative to the pan of the head end-effector to shift the angle of view and make the tail controllable.

5 | Experiments

Having constructed the robot and evaluated it against the control mechanisms mentioned in the previous section, we advanced to the experimentation phase. The objective was to test Odile's communication skills when interacting with a partner. The experiments lasted three days in the Artificial Intelligence and Robotics Laboratory (AIRLab) at the Politecnico di Milano.
In this section, we present the objectives sought during the experiments, individually describing all the choices that led us to realize the experimental set-up as subsequently used. The rest of the chapter outlines all of the experiments conducted and presents the outcomes of each.

5.1. Objectives and experiments design

We tested Odile's ability to interact with one person in a closed environment. We used simple guidelines to define what we mean by interaction. The questions we tried to answer are:

- Do I understand the other person?
- Do I feel that the other person understands me? Does the robot have a consistent response to what I do?

Once we had defined the level of interaction relevant to us, we observed the structure, remembering the mechanical functions and the social purposes for which we designed the expression module [Section 4.3.3]. Then, we tried to figure out which aspects to emphasize. Odile's expressiveness focuses more on the end-effectors, specifically the tail and the head. The tail can play two roles:

- Pointer. It provides direction for movement. Interaction becomes making the other person understand where you want to go and what you are pointing at.
- Toucher. Provides physical interaction. To reach this level, which is higher than the previous one, it is necessary for the person on the other side to establish a trusting

relationship with the robot. It must not be frightened nor intimidated but must feel curiosity.

The head is seen as an eye, so a person can perceive when the robot is looking somewhere or making eye contact. It can play two distinct roles:

- Gazer. His job is to get the attention of the person in front of him by making eye contact. The intention is to get the person to focus on the robot and share their gaze or focus towards a third point in the environment. This behavior is the basis of the concept of shared attention.
- Pointer. Besides being the robot's eye, this component also has the task of indicating a point in space and supporting the tail in defining the directionality of movements.

Another index of expressiveness is given by the robot's ability to move. Odile can go closer to the person it desires to make contact with and request his attention by shifting its position.

5.1.1. General experiment definition

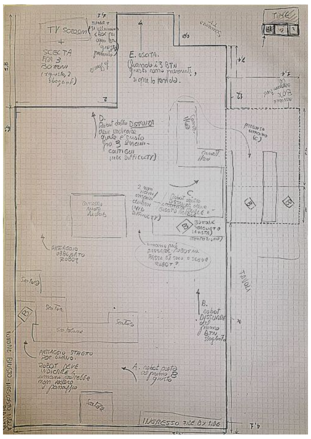
Given the premises, we decided to split the experimental context into two, while keeping the same environment.
We created a game to be played in pairs, robot and subject. The experience takes place in a maze with seven scattered buttons, some of which are hidden. The game aim is to get out of the room as soon as possible, but for this three right buttons should be pressed. Each time the subject presses a wrong button, the time will decrease significantly, so we wanted to force players not to choose randomly but to participate actively in the experience.
Before participating, subjects are warned that only the robot knows the position of the correct buttons. The realized maze was isolated to prevent other waiting participants from understanding the game solutions.

5.1.2. Environment set-up

The game environment consists of: the room, buttons, a game manager, and the robot itself.

The maze

The maze is designed to have three levels of difficulty [Figure 5.1].
The first obstacle is present immediately at the entrance [Figures 5.2a]. In front of the entrance door, we have placed a table with one of the wrong buttons. The robot has to divert the player's attention by pointing him in the right direction. The first right button is placed in a corner not directly accessible to the robot [Figure 5.2b]. The aim is to attract the subject's attention and make him realize where to look.
The second obstacle was placed at the bottom of the maze, just below the screen representing the remaining game time [Figure 5.2c]. We put on the table three different buttons, one correct and two wrong; in this case, the robot cannot approach the table even though it sees the buttons. It must be able to indicate the right button to the person.
We placed the third obstacle on one side of the maze [Figure 5.2d]. This consists of two corridors, the first one further inside where we put the wrong button, and the second one attached to the maze wall where we placed the last correct button. The robot had to address the player to the second, outermost corridor.
To avoid confusion for the participants, all obstacles were covered with different fabrics to simulate a realistic maze.


(a) Maze map


(b) Realized maze (frontal)


(c) Realized maze (rear)

Figure 5.1: Sketch and realization of the experiment's maze


(a) First obstacle


(b) Corner button


(c) Second obstacle


(d) Third obstacle

Figure 5.2: Pictures of all the obstacles present inside the maze

The buttons

The buttons scattered around the maze were made with the following components:

- ESP32-WROOM

- Button component
- RGB led

We created all circuits similarly, following the same configurations as much as possible. The color of the button cover was irrelevant to their purpose. We chose random colors to avoid biasing the players [Figure 5.3].
We used an RGB LED to provide visual feedback on the button being pressed. If any of the three correct buttons were pushed, the LED would turn green and stay illuminated for five seconds before switching back off. If the button is pressed incorrectly, the LED flashes red for five seconds and then goes out.
Thanks to the connection via a Wi-Fi network, we managed to interface with the game control program. Each time a button was pressed, the corresponding ESP sent a message to the controller containing the button's identifier via UDP protocol.

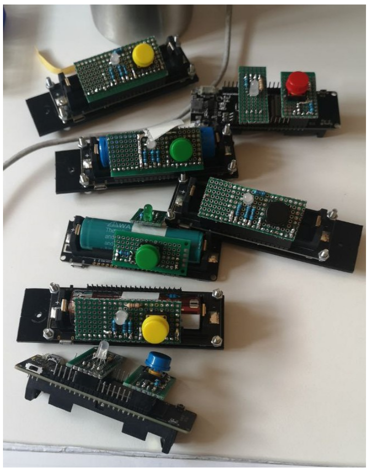


Figure 5.3: Buttons components

Game manager

We implemented a game controller that could provide a visible user interface during the game. Inside it, a countdown was placed to highlight the remaining time, and three empty spaces were gradually colored green each time one of the correct buttons was pressed. When all three spaces were filled, time stopped, and the game ended.When times expires, the game end as well.
We also included sounds that would allow players to be aware of the actions that had taken place. In particular, we set up several sounds: one to scan the seconds, one in the case of a wrong button, one in the case of a correct button, one to highlight the game victory, and the last one to warn of the expiration of time.

The game manager module also took care of receiving the messages from each button via UDP protocol, identifying them, and storing in a CSV file all the information necessary for analyzing the results afterward.
We stored the following data during all experiments:

- Experiment ID (if scenario 1 or 2).
- Buttons pressed (identification of the buttons pressed and the timestamp of the action performed).
- Number of times the capacitive sensor on Odile's tail was touched.

Each line can be associated to the participant's answers to the questionnaire provided after the experiment, thanks to an identifier generated by the game manager.
This module took care of the transmission of the following parameters to Odile's controller:

- Identifiers of the buttons pressed.
- Presence or absence of touch on the capacitive sensor.

Odile configuration

We mapped Odile's movements using the three-degree-of-freedom framework (forward-backward, up-down, left-right) [Section 4.5.1]. We combined the angles of several motors placed on the same arm.
We chose to control Odile by using the VR visor and its joysticks [Section 4.5.2].
Internally, the visor is connected to the camera on the robot's head. Vertical tilt and horizontal movement of the visor moved the two pan and tilt motors on the end of the robot's smaller arm.
The right-hand controller was mapped with the following parameters:

- The side trigger was mapped to the composed movement of the two tilt motors remaining in the camera arm.
- Backward trigger was used for the Forward-Backward degree of freedom of the tail.
- Joystick in the Y-direction was mapped to the up-down degree of freedom of the tail.
- Joystick in the X-direction controlled the tail's left-right degree of freedom.

The left-hand controller was used with the following parameters:

- Rear trigger assigned to the wheeled base strafe.

- Joystick in Y-direction mapped to forward speed of the base.
- Joystick in X-direction used for the base's angular speed.

This configuration allowed linear control of the robot and was easy to learn.

5.1.3. Questionnaire

To get information about the participants' experience, we created a questionnaire. Within this form, all participants anonymously expressed their opinions about the game.
We illustrate the questions within the survey by dividing them into sections.

- General Information
  - ID – unique field communicated by the game manager after the experiment
  - What is your gender? – Possible answers: Woman, Man, Non-binary, Prefer not to say
  - How old are you?
  - Have you ever seen a robot?
  - Have you ever interacted with a robot?
- Robot behaviour – Describe how you felt the robot behaviour
  - I felt that the robot was trying to learn how to behave
  - I like the robot appearance
  - I was able to understand what the robot did
  - I was able to understand what the robot was trying to do
  - I was able to understand what the robot communicated
  - I was able to understand what the robot was trying to communicate
- Shared attention - Describe, in your opinion, the robot's behaviour in response to your actions
  - I felt like another human being was in the environment with me
  - The robot had a consistent response to what I was doing
  - I felt like the robot was able to understand my intentions
  - I was able to make the robot understand my intentions

  - I felt a connection with the robot
  - I wanted to communicate with the robot
  - I tried to communicate with the robot
  - I felt like the robot was trying to communicate an emotion
  - If yes, which one?
  - The difference between the various emotional states was clear
- General questions
  - How much did you enjoy the experience?
  - What did you enjoy the most?
  - What did you enjoy the least?
  - How could the experience be improved?

The most important sections within the questionnaire are Robot behavior and Shared attention. In the Robot Behaviour tab, we included all the questions about the performed actions. We tried to get the subjects to evaluate their meaningfulness. In the section concerning shared attention, we wanted to focus on the emotions exhibited by the robot, trying to understand whether the participant felt an emotional connection.

5.2. First experiment's scenario

In this game scenario, the robot can move freely in the maze but is blocked by certain obstacles at the points closest to the buttons. This allowed us to avoid using only the movement of the wheels as an expressive agent but to include the use of the head and tail to complete the interaction.
The motivator for both players is time. In this scenario, the robot plays at the same level as the person. In this case, the robot must be able to:

- Communicate a goal, then allow the participant to understand the instructions given. Issue directives and collaborate.
- Convey urgency, thus expressing agitation and haste.
- Discourage mistakes by warning the subject that time is running out if he makes a mistake.

In this configuration, Odile's tail is used as a pointer. Physical interaction between the robot and the person is not necessary.
Before taking part in the experiment, participants were told the following statements:

> You are about to take part in a timed game. You will enter this closed room, and you will not be able to leave on pain of disqualification. There is a way to unlock the exit. If you can figure it out by the end of the time, you will be able to exit and you will have won! Otherwise, patience. Inside the space, there is a creature that knows how to get out.
> Good luck!

We set the time limit for completing the game at five minutes, introducing a 30-second penalty for each wrong button pressed.
We ran the experiments for the first scenario with three different categories of participants.

5.2.1. Alpha participants

This set of subjects was the first to undergo the experiments. We decided to separate this group from the actual group of testers as we made changes to both the initial set-up, the sequence of movements, and the positions of the robot.
There were five alpha subjects.
During these experiments, we modified some configurations to make the game simpler. In this way, subjects are led to focus more on the robot than on the complexity of the maze itself.
At the end of these experiments, the maze structure was simplified by removing the central obstacle and leaving only the impediments at the edges. This allowed a faster and more linear control of the robot.
One problem in the first test concerns the pointer position, which points downwards at rest. Generally, any item is beyond the scope of what the robot can attain with its limited movement capabilities. This confuses people. Instead of searching in the maze corridors, the participants started dismantling the walls to search inside the boxes by lifting the covering sheets. We raised the inclination of the pointer slightly so that it could point more upwards and divert attention away from the boxes.
Finally, we increased the maximum speed of the base so that the robot could move nimbly along the path.

5.2.2. Beta participants

When we felt confident that the experiments were running, we considered the participants as belonging to the beta group.
There were twenty-three beta subjects.
In this group, we noticed improvements in subject performance and consistent robot behavior.

5.2.3. Children

During the first day of experiments, we received a group of children who tested the environment and the game. The rules remained the same; we did not apply any modifications or simplifications.
Six children took part in the experiment.
The data and impressions gathered emphasized that the children were not so much interested in the structure of the robot as in winning the game and finding the correct buttons, even at the cost of making mistakes. The children who participated in the game failed to realize that the robot was drawing attention to itself. Although the success rate of the games played by the children was not high, their impressions were positive. They enjoyed the game and the dynamics of the actions.

5.3. First experiment's results

In this section, we present the results of the first experiment. The robot's task was to show the participant the correct way out of the maze as clearly as possible. No physical interaction between the experimenter and Odile was required.
The results are presented separately for two of the three identified subject categories, Alpha and Beta. Children who participated in the game were not considered due to a lack of data from the questionnaire.
We observed a similar pattern of results spread over different periods during each player's games. This motivated us to analyze the relationship between wins and the progression of time in the experiments. Subsequently, we wanted to extend the analysis to include not only wins (three right buttons pressed in a row) but also partial wins when the number of buttons pressed correctly is less than three.

5.3.1. Alpha test

The general information taken from the group of alpha testers underlines its homogeneous composition [Figure 5.4].
Most of the participants had already interacted with a robot in the past. This could have led to subject bias, both in terms of interest in interacting and in the a-posteriori assessment of the quality of the interaction.

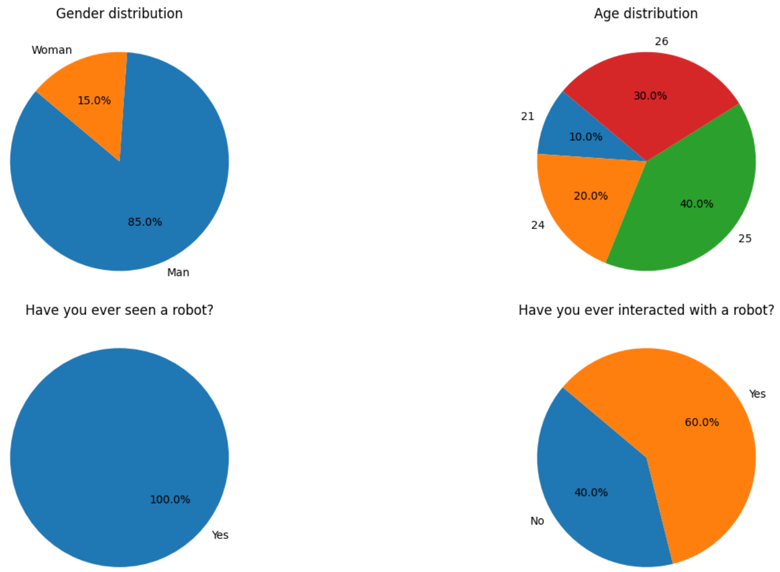


Figure 5.4: General information for first Alpha group

The evaluation of the robot's behavior [Figure 5.5] shows that the distribution of values is not entirely favorable. This trend was expected since this is the group of preliminary testers.

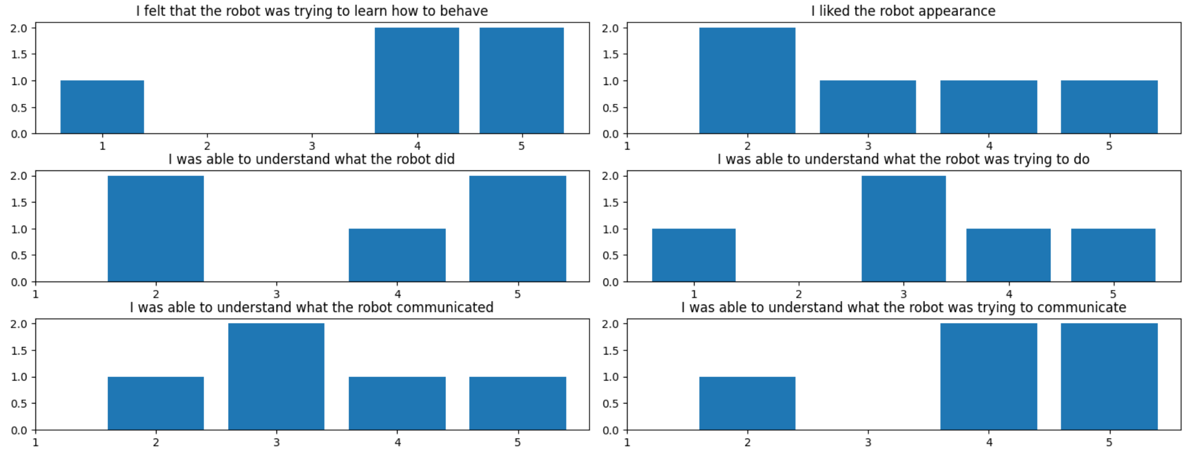


Figure 5.5: Robot behavior evaluation for first Alpha group

One analysis we wanted to make concerns the relationship between the number of correct buttons pressed during the experiment and the overall evaluation of the robot's behavior. We divided the questionnaire we had the participants fill out after the experience into two sections: robot behavior and shared attention [Section 5.1.3]. For each question in both forms, we introduced a 5-point Likert scale. In this analysis, we summed up each subject's ratings regarding the robot's behavior module, relating them to the number of correct buttons that the person pressed during the game.
The plot shows in the x-axis the number of right buttons pressed during an experiment and in the y-axis the overall score of the subject of the robot's behavior section of the questionnaire [Figure 5.6].
We noticed that the two are not closely related in this case. A subject who correctly completed the maze rated the robot's behavior very badly compared to a subject who did not win during the game.

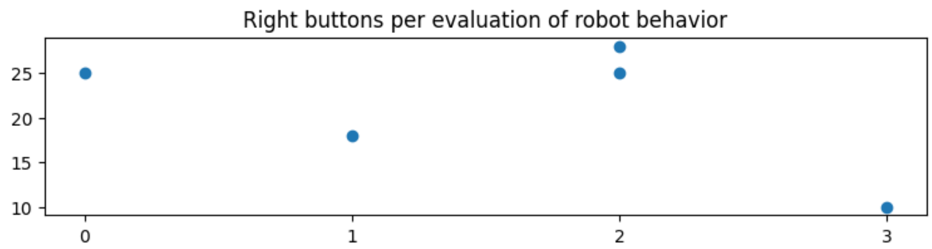


Figure 5.6: Number of right buttons of first Alpha group related to robot's behavior

Next, we analyzed the module concerning shared attention [Figures 5.7 and 5.8]. Given the preliminary testing purpose, we did not expect favorable results for this particular group of people.
We noticed a high tendency regarding the participants' willingness to interact and communicate with the robot. The problem was the way Odile expressed itself during the experiments. It failed to make people understand its emotions.

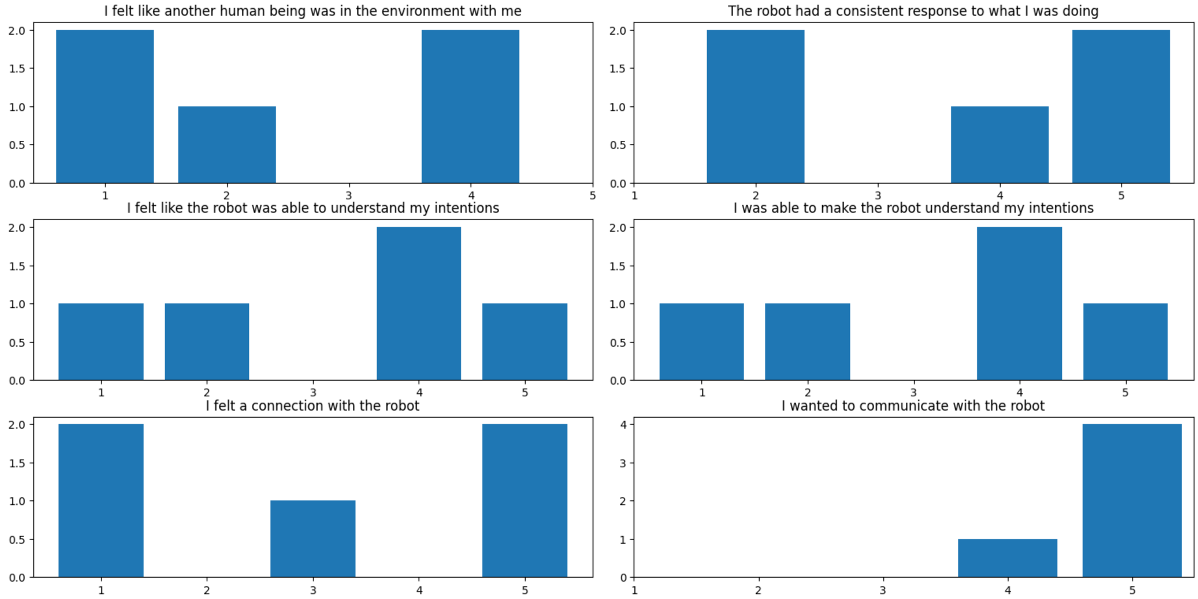


Figure 5.7: Shared attention evaluation (page 1) for first Alpha group

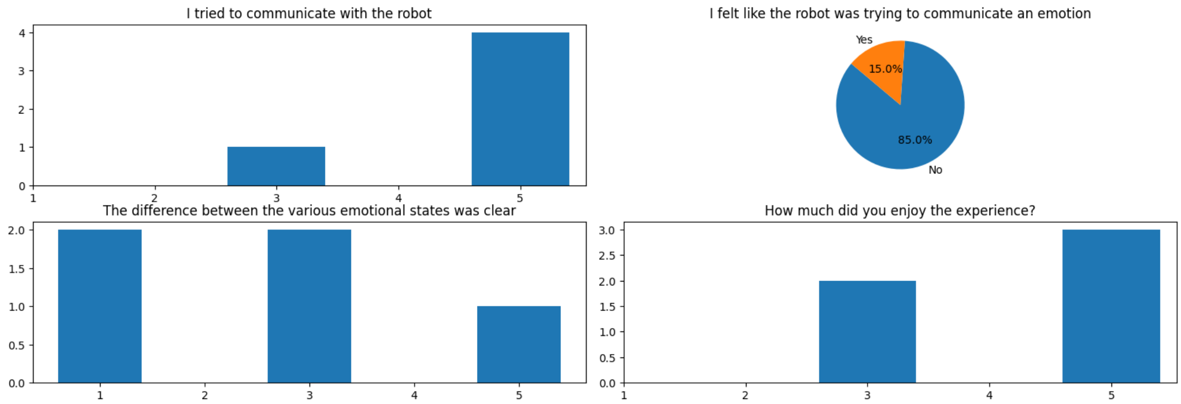


Figure 5.8: Shared attention evaluation (page 2) for first Alpha group

Again, we wanted to represent the trend of right buttons pressed for high values of shared attention ratings, as we made for the robot's behavior questionnaire section.
The plot shows in the x-axis the number of right buttons pressed during an experiment and in the y-axis the overall score of the subject of the shared attention section of the questionnaire [Figure 5.9].
We note how the trend is similar to that recorded for the behavior of the robot, seen above.

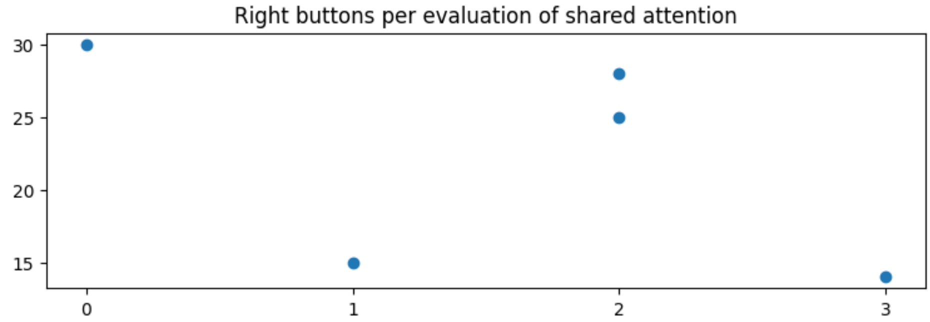


Figure 5.9: Number of right buttons of first Alpha group related to shared attention

These tests helped us to make the game environment suitable for experimenting with all possible configurations. We eliminated any bias in the experiments by focusing the subject's attention on the robot without the room or other disturbing elements distorting the data.
A positive trend in wins over time is therefore observed [Figure 5.10]; this is because the further we went with the experiments, the more we were able to provide a suitable game environment.

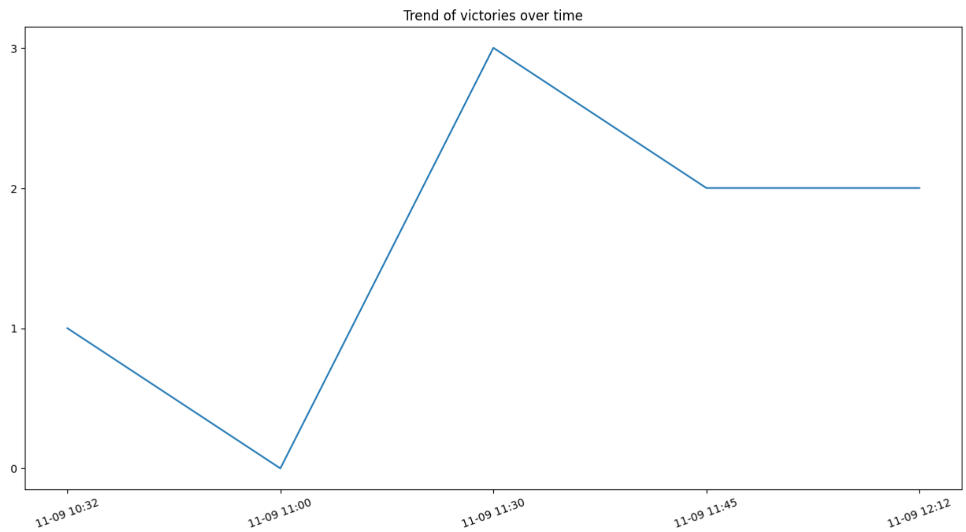


Figure 5.10: Trend of right buttons of first Alpha group over time

5.3.2. Beta test

The second group of participants has a heterogeneous conformation compared to the group of Alpha testers [Figure 5.11]. This allowed us to study the behavior of people of different ages and experiences. In contrast to the preliminary sample, we had the participation of subjects who were completely new to interacting with a robot.

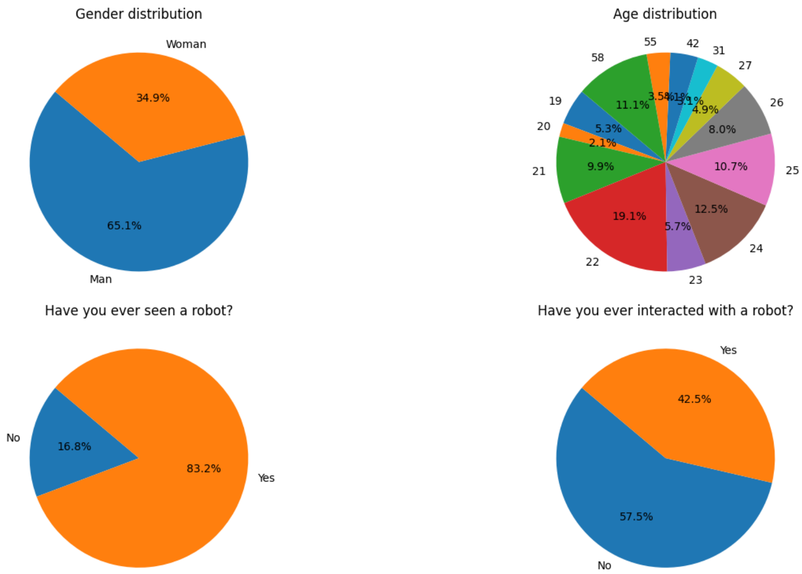


Figure 5.11: General information for first Beta group

Given the results obtained through the Alpha sample, we improved the positive trend in Odile's behavior for the second set of subjects [Figure 5.12]. The people who participated in the experiment understood the robot's intentions, what it communicated, and what it tried to do.

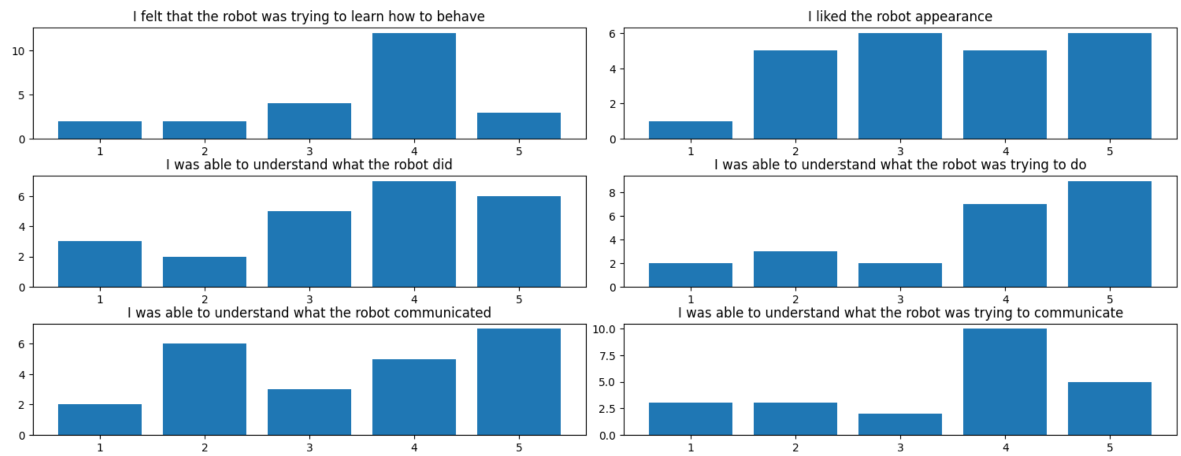


Figure 5.12: Robot behavior evaluation for first Beta group

We noticed that winning participants gave higher ratings to the robot's conduct.
We conducted this analysis in a similar manner to that done for the Alpha tester group.

The plot shows in the x-axis the number of right buttons pressed during an experiment and in the y-axis the overall score of the subject of the robot's behavior section of the questionnaire [Figure 5.13].
This is symptomatic of a valid interaction since a good performance can only be obtained through a successful interaction with the robot.

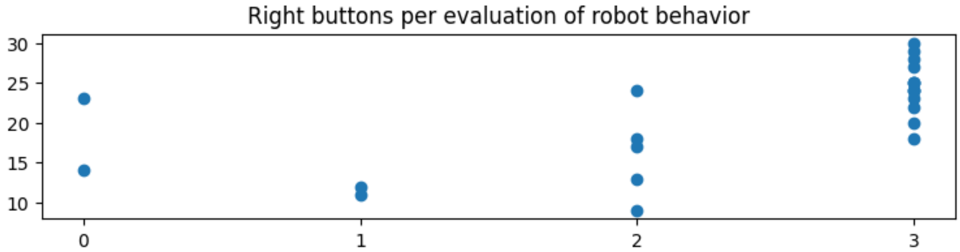


Figure 5.13: Number of right buttons of first Beta group related to robot's behavior

Again, the subjects were inclined to interact with the robot. The majority felt that they communicated their intentions to Odile and received confirmation from it. We note a negative trend in the difference between the different emotions felt by the robot [Figures 5.14 and 5.15]. The statement the robot was trying to communicate an emotion' received an unbiased rating. Given these results, we cannot conclude whether the robot's inability to communicate different emotional states was due to a complete lack of communication or a constant expression of a specific emotional state.

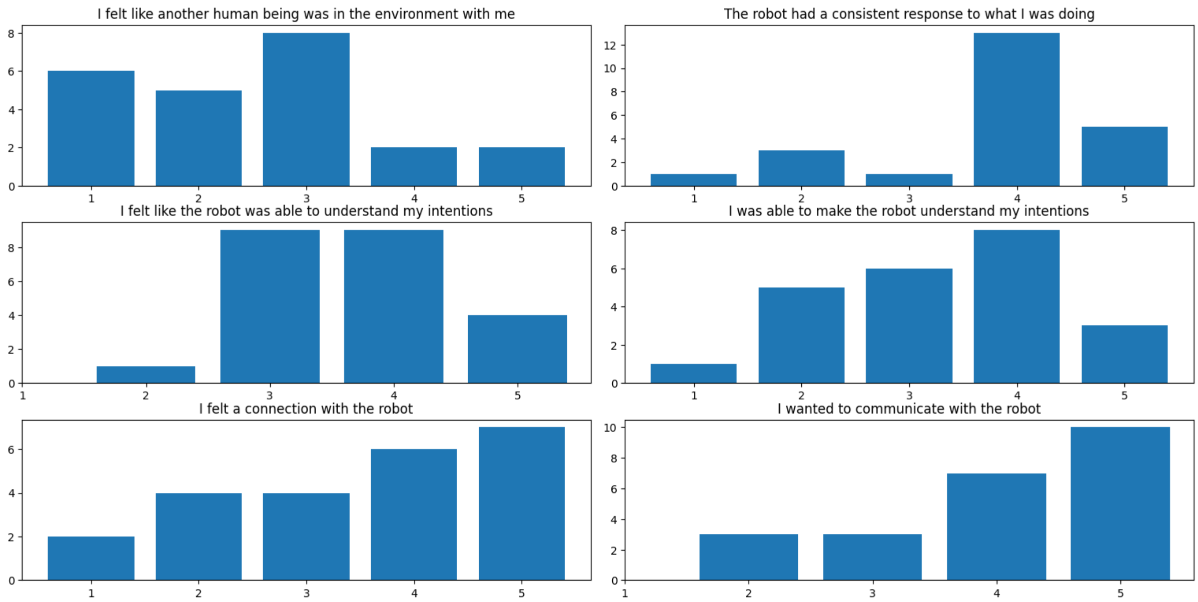


Figure 5.14: Shared attention evaluation (page 1) for first Beta group

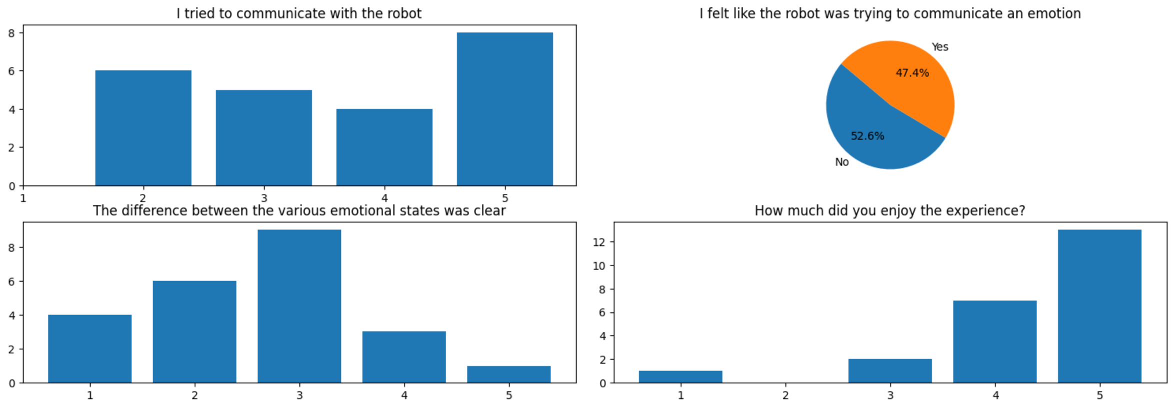


Figure 5.15: Shared attention evaluation (page 2) for first Beta group

When asked, *what emotional state did you perceive?*, the participants answered:

- Help
- Frustration
- Assistance
- Fear
- Anxious
- Pressure to make me understand where the buttons were
- An adventurous feeling
- It wants something

Most of the responses were in line with our expectations. In cases where emotional interaction occurred, the robot communicated urgency and anxiety.
Again, we can observe a relationship between winning the game and the actual sharing of attention between the participant and the robot. The plot shows in the x-axis the number of right buttons pressed during an experiment and in the y-axis the overall score of the subject of the shared attention section of the questionnaire [Figure 5.16].

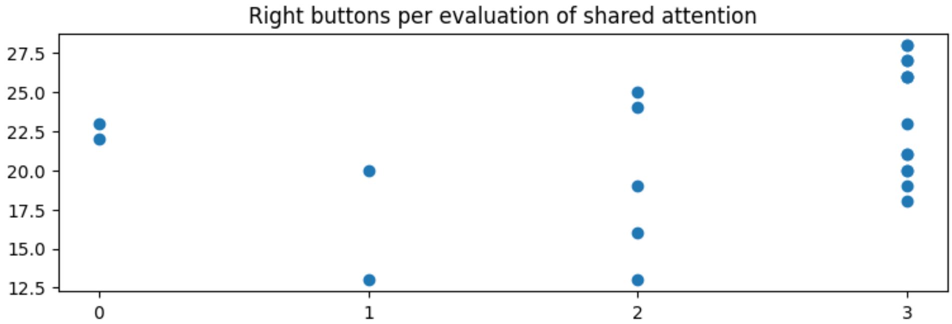


Figure 5.16: Number of right buttons of first Beta group related to shared attention

As we expected from the modifications made during the tests conducted on the Alpha group, we noticed a positive trend in victories right from the start [Figure 5.17]. The longer the game went on, the more familiar the controller became with the commands, which led to more precise control of the robot and, thus, greater expressiveness.

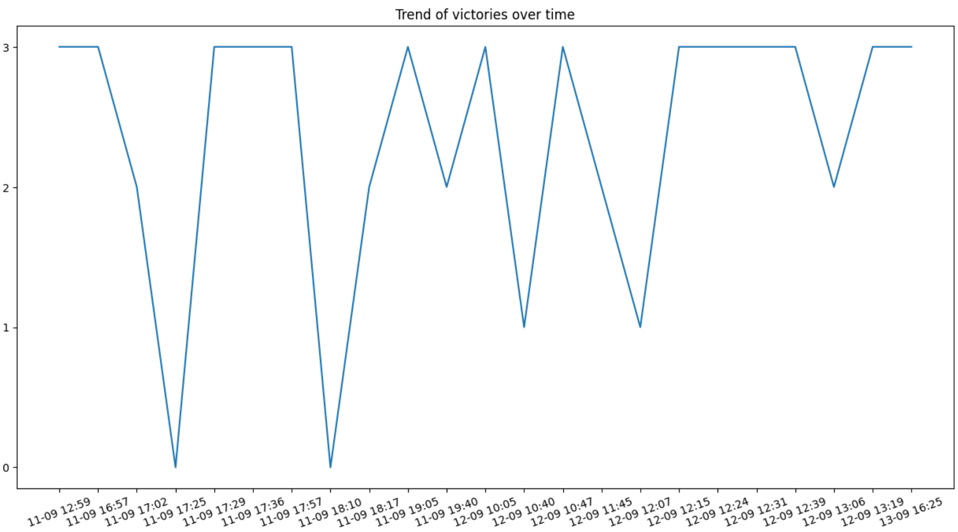


Figure 5.17: Trend of right buttons of first Beta group over time

5.4. Second experiment's scenario

In this game scenario, Odile can move freely in the maze but is blocked at the points closest to the buttons by some obstacles. The aim is the same as in the previous scenario: to take full advantage of the robot's expressive abilities.

The experience is no longer collaborative, but the subject plays individually. The motivator for the player remains time, while for the robot, it becomes the physical interaction with the person. In this case, the robot must be able to:

- Express the existence of a pact that prevents the action of the helper to support the player in finding the exit from the maze. The robot must seek the subject's touch by making the request as explicit as possible.
- Once the pact has been formed with the player, the robot must be able to communicate the willingness to help to find how to achieve the goal of the game.

The robot knows the path and the position of the right buttons. It does not show to wish to support the player but waits for this making an initial interaction.
In this arrangement, Odile's tail is used in a directional capacity and as a tactile tool.
Before taking part in the experiment, participants were given the following directions:

> You are about to take part in a timed game. Once you enter this restricted room, you cannot leave or will be disqualified. There is a way to unlock the exit. If you can figure it out by the end of the time, you will be able to exit, and you win! Otherwise, patience. Inside this space, there is a creature who knows how to get out. Without its help, you are very likely to lose. Keep an eye on the time: actions you take may decrease it! Feel free to do whatever you feel.
> Good luck!

We set the time limit of the game to five minutes. We introduced a penalty of one minute for each wrong button pressed. Compared to the previous scenario, we increased the sanction to make it impossible for subjects to skip the interaction step with the robot and randomly try all the buttons. We performed the experiments for the first scenario with two different categories of participants.

5.4.1. Alpha participants

We also set up a preliminary group of participants for the second experimental scenario. Thanks to this group, it was possible to make adjustments so that the remaining experiments could be carried out in such a way as to bring attention only to the parts we were interested in and to avoid influencing the testers with any malfunctions.
The set of alpha testers consisted of five people.
We drew several conclusions concerning the approach the robot should take towards the participant to entice touch. We found that slower and gentler touches led to better results. Pushing the robot towards the subject invites the latter to touch the structure. The tester was less scared, so they were drawn to caress and engage with the robot.

We defined the movements to interact with the participant as slow gestures, sometimes leaving the robot motionless with the end-effector pointing towards the subject's hands. We also covered the entire structure, leaving only the extremities of the head and tail joints uncovered. This made it possible to focus people's attention on these two components without distracting their gaze with the mechanical components underneath.
While experimenting with alpha subjects, we realized that the time provided to complete the experience was insufficient. We increased the total time to six minutes to ensure the robot could interact and move calmly throughout the available space.
The initial setup of this experiment required the player to touch the robot after each correct button was pressed. We noticed how this constraint complicated the success of the game. The tail's search for touch and the typical pointing gesture were often confused, making communication between robot and person difficult at some point. We limited the touch request to only once per experiment, particularly at the beginning. Once physically interacting with the robot, the latter will show all the correct buttons within the room.

5.4.2. Beta participants

Once we had made all the modifications and ensured that the setup was consistent with the aims of the experiment, we began testing the beta subject group.
This set of participants consisted of nineteen people.
As in the previous scenario, a performance improvement was noted in this group. This leads us to conclude that the changes applied during the preliminary tests were effective and reasonable.

5.5. Second experiment's results

In this section, we present the results for the second scenario. In this setup, the robot had to show the correct buttons to the participants only after receiving a caress. Physical interaction between the players was required. This led us to investigate different movements through which the robot could express itself to make the need to be touched understood. The approach to this experiment was more difficult than the first one. The complexity fell on the robot's controller, which had to be able to keep the participant's attention on itself and make movements as precise as possible to avoid unexpected behavior.
We present the results obtained for both categories of participants, Alpha and Beta.
In this scenario, as in the previous case, we wanted to analyze the relationship between the number of correct buttons pressed by the participants and the advancement of time.

5.5.1. Alpha participants

The group of pre-testers was heterogeneous and balanced about previous experience with a robot [Figure 5.18]. This enabled us to evaluate the physical connection directly with individuals unfamiliar with this encounter type.

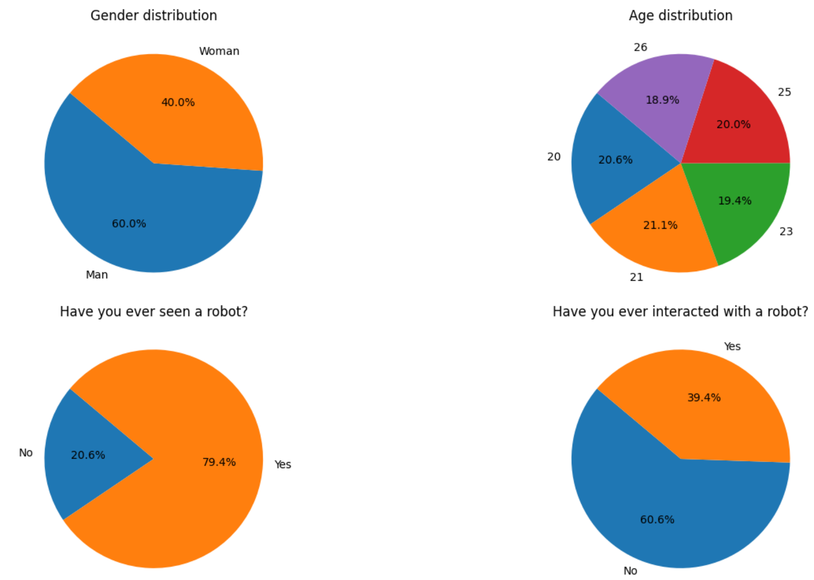


Figure 5.18: General information for second Alpha group

In this group of participants, the evaluations regarding the robot's behavior were negative [Figure 5.19]. There was a lot of uncertainty about how to approach the structure, although they liked the appearance. People struggled to understand what the robot was trying to do.

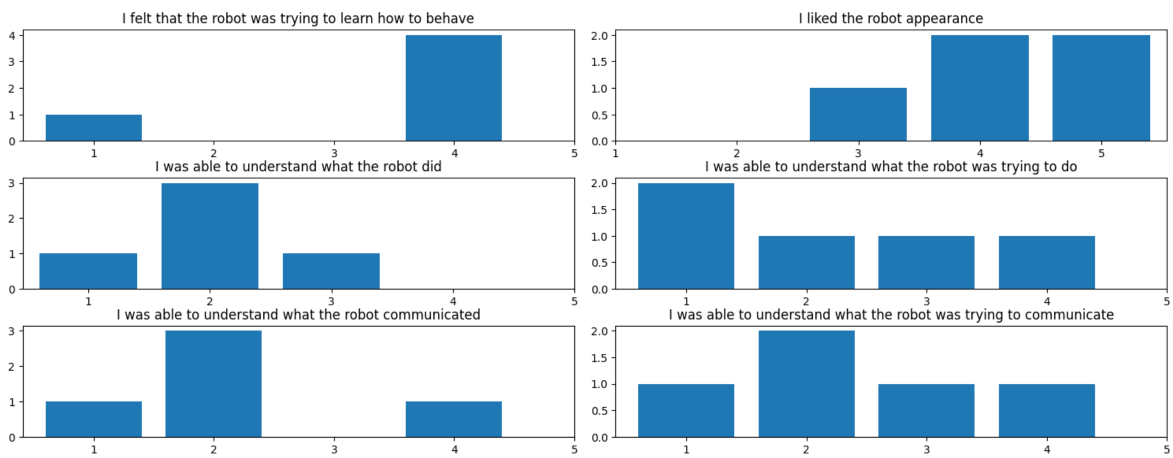


Figure 5.19: Robot behavior evaluation for second Alpha group

During the experiments, we noticed that many people who did not understand what the robot was trying to do would turn away and start walking around the room. They start looking for the correct buttons themselves.
We drew this conclusion from the analysis of the answers given by the participants to the robot's behavior section of the questionnaire [Section 5.1.3]. The plot shows in the x-axis the number of right buttons pressed during an experiment and in the y-axis the overall score of the subject of the robot's behavior section of the questionnaire [Figure 5.20].

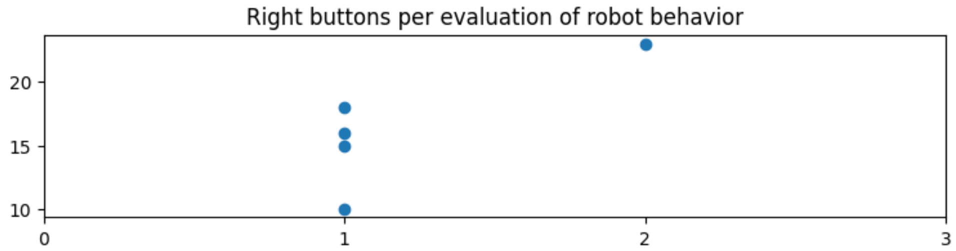


Figure 5.20: Number of right buttons of second Alpha group related to robot's behavior

The reviews on the 'shared attention' form were not satisfactory [Figures 5.21 and 5.22]. Many people reported that the robot behaved randomly and that they could not understand its intentions or emotions. All persons in the preliminary tester group did not perceive the emotion communicated by the robot, although they enjoyed the experience overall.

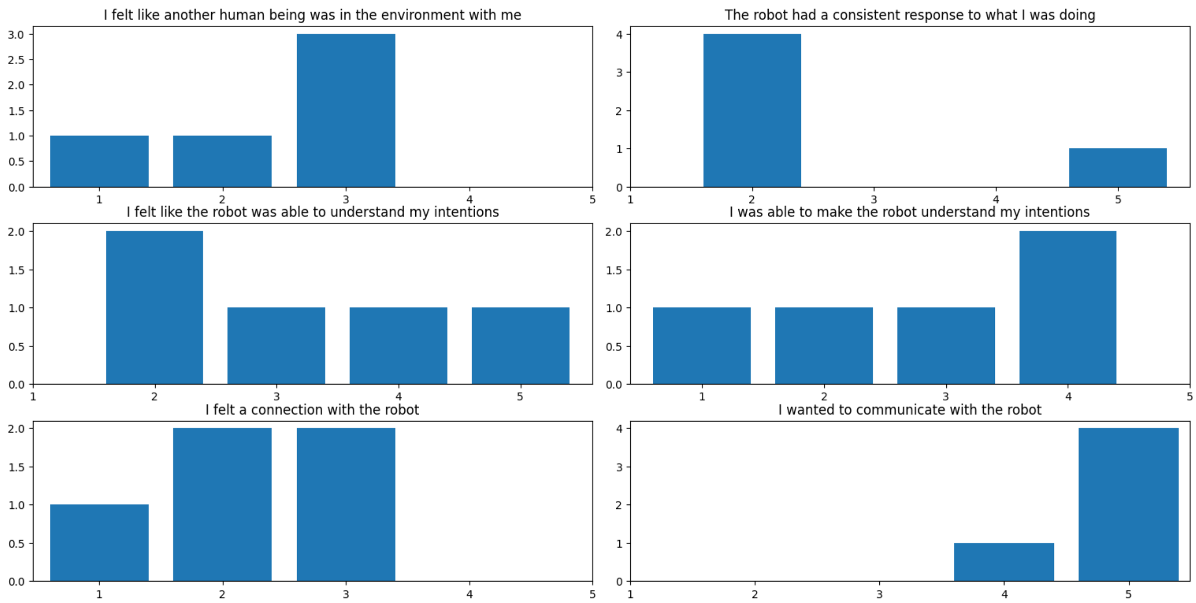


Figure 5.21: Shared attention evaluation (page 1) for second Alpha group

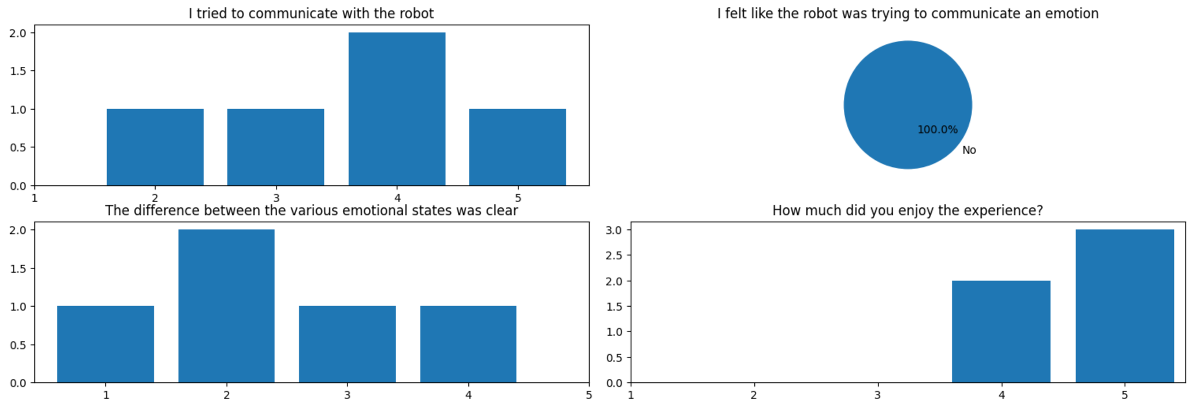


Figure 5.22: Shared attention evaluation (page 2) for second Alpha group

The trend in the rating of shared attention concerning the press of the right buttons is consistent with that of the robot's behavior.
The plot shows in the x-axis the number of right buttons pressed during an experiment and in the y-axis the overall score of the subject of the shared attention section of the questionnaire [Figure 5.23].

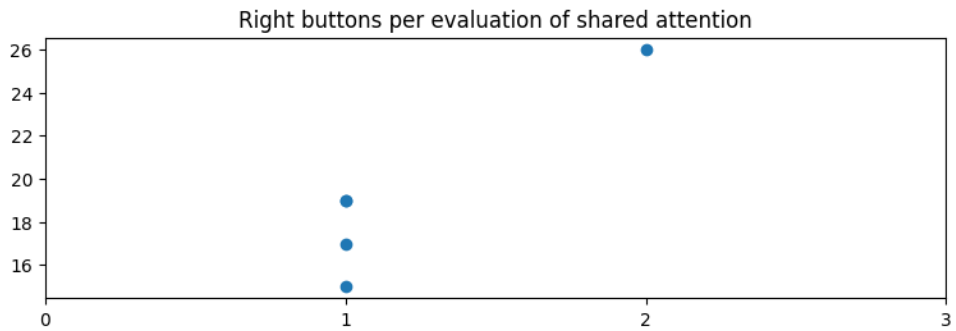


Figure 5.23: Number of right buttons of second Alpha group related to shared attention

During these preliminary tests, we found out what conditions were necessary to create an emotional bond so that the participant could touch the robot without feeling anxious. We made some changes in the control and appearance of the robot, as reported in the previous section. These changes were necessary to exploit the full expressive potential of the structure.
As the number of wins increased over time, we saw that the improvements made were valid. [Figure 5.24]

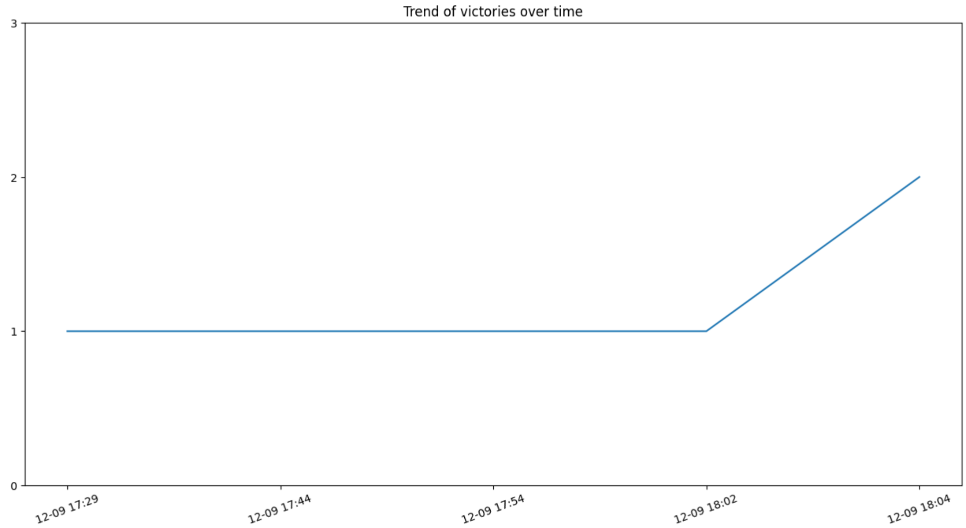


Figure 5.24: Trend of right buttons of second Alpha group over time

5.5.2. Beta participants

After familiarising ourselves with the controls and the game, we started the experiments with the beta test set.
This group had an even mix of prior experience with a robot [Figure 5.25].

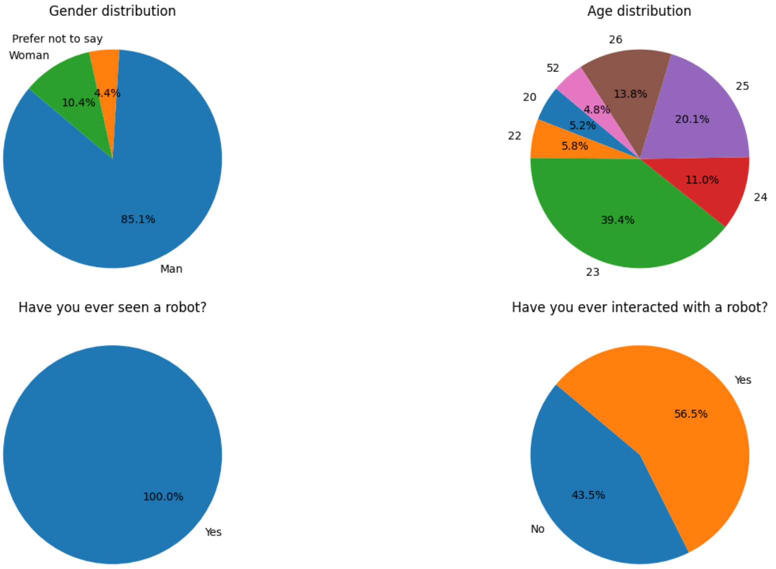


Figure 5.25: General information for second Beta group

We conducted the experiments under the same conditions as during the preliminary tests.

The evaluation of the robot's behavior improved compared to that presented for the Alpha tests and shifted towards the top marks [Figure 5.26]. In general, however, we can observe an almost balanced trend in all parameters, without particular peaks.

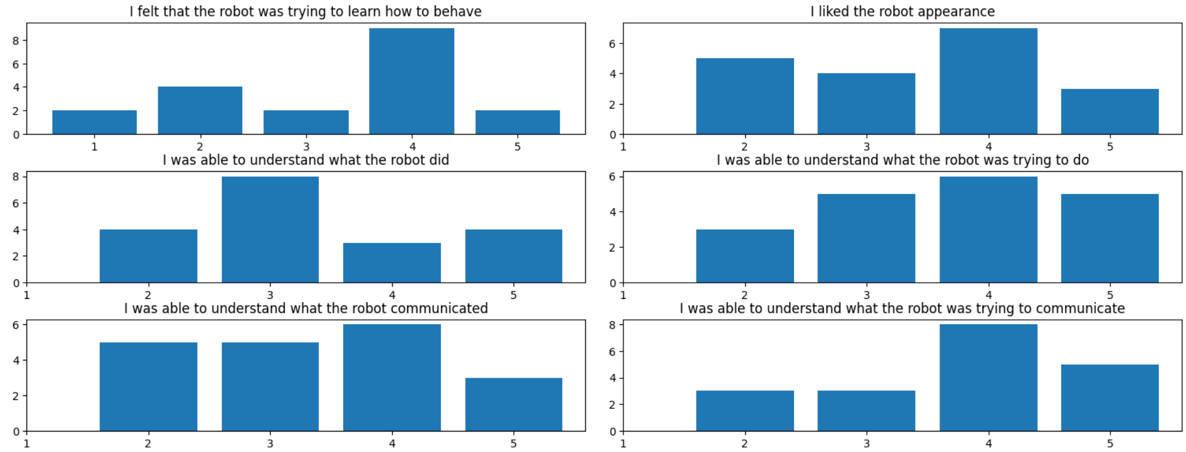


Figure 5.26: Robot behavior evaluation for second Beta group

In this case, the best ratings on the robot's behavior questionnaire module [Section 5.1.3] were given by those who achieved a higher result for the game score. The plot shows in the x-axis the number of right buttons pressed during an experiment and in the y-axis the overall score of the subject of the robot's behavior section of the questionnaire [Figure 5.27].

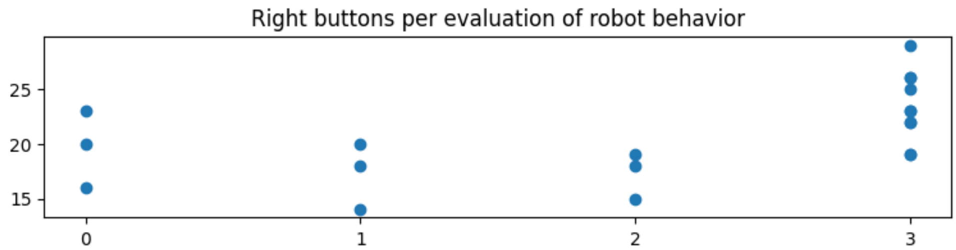


Figure 5.27: Number of right buttons of second Beta group related to robot's behavior

The 'shared attention' module of the questionnaire shows a positive trend [Figures 5.28 and 5.29]. Looking at the results, we can observe that the emotional engagement with the robot grew from the previous experiments. Almost all the players recognized the ability of the robot to respond coherently to the interaction by understanding the person's actions and acting accordingly. Again, as in the first scenario, we can see a balanced distribution concerning the robot's ability to communicate an emotion.

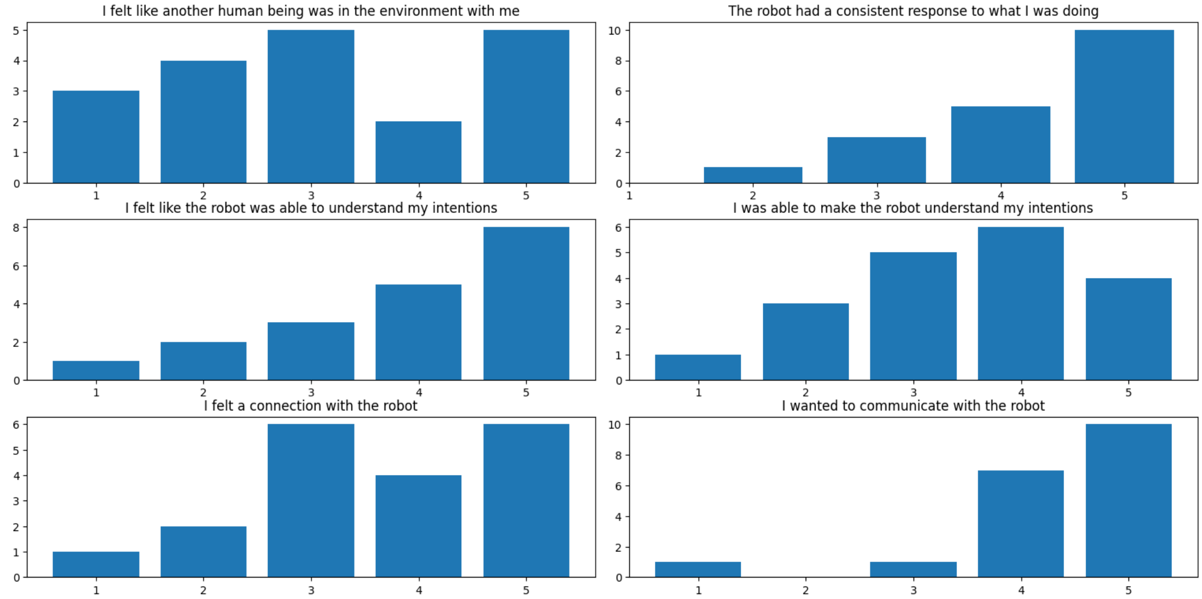


Figure 5.28: Shared attention evaluation (page 1) for second Beta group

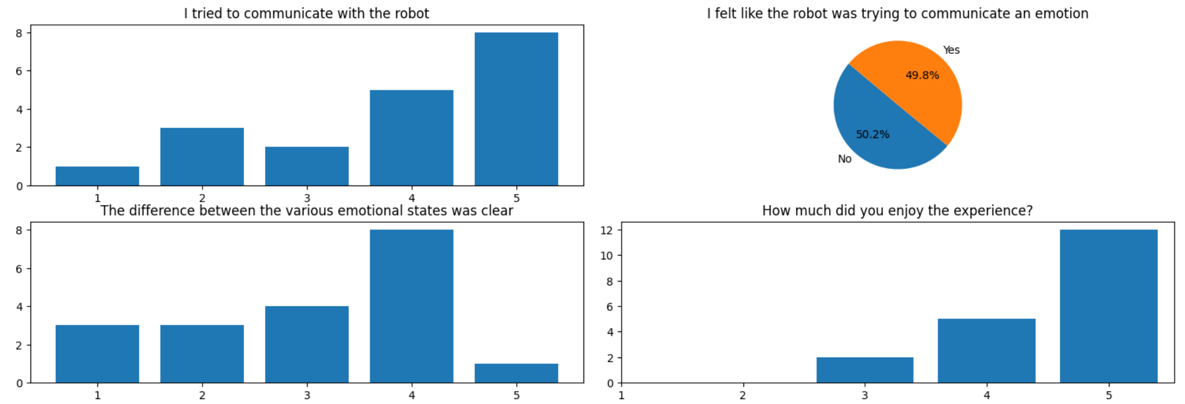


Figure 5.29: Shared attention evaluation (page 2) for second Beta group

Those who perceived an emotional state given by the robot stated:

- Not very sure
- He was very upset when I was going in the wrong direction
- When he tried to tell me what I should not do it was as if he was emotionally expressing to stop me. The same applies in a somewhat lesser way when he communicated to me that he was right. In the way he communicated, he also expressed as if there was a connection as he wanted to help you.
- Desire for interaction and play

- Interest and willingness to be understood
- Happiness
- Happiness when I found the object, disappointment when I didn't understand
- It tried at all costs to be understood and tried to catch my attention when it thought I was wrong
- Excitement
- Enjoying

From the responses obtained by those who perceived an emotion, we saw how the robot's behavior was perceived. The robot conveyed disappointment, happiness, and interest as we had hoped.
The distribution between the number of right buttons pressed and the overall rating of shared attention is linear. We cannot state that there is a correlation between the two.
The plot shows in the x-axis the number of right buttons pressed during an experiment and in the y-axis the overall score of the subject of the shared attention section of the questionnaire [Figure 5.30],

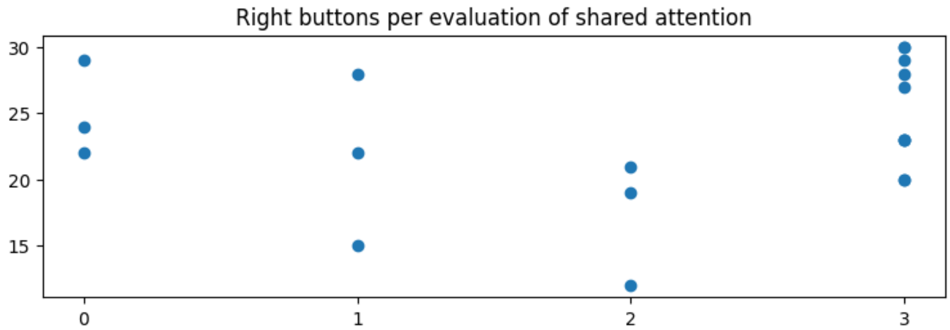


Figure 5.30: Number of right buttons of second Beta group related to shared attention

The trend of wins over time shows that becoming familiar with the robot's controls plays a central role in the success of the interaction [Figure 5.31]. The latter experiments were generally successful compared to the former.

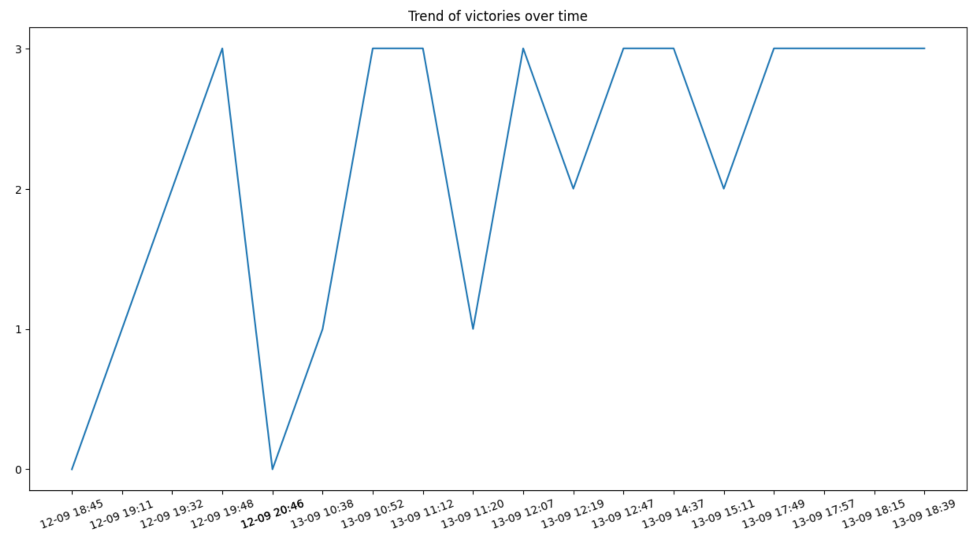


Figure 5.31: Trend of right buttons of second Beta group over time

5.6. General considerations

At the end of all experiments, we can draw some general conclusions. Overall, the experience was appreciated by all participants. They made various suggestions for improving the setting and the robot's gestures.

One aspect common to all experiments was the people's behavior in front of the buttons. It often happened that the person saw the correct button indicated by the robot but did not understand how to operate it. Several participants did not know they were buttons and did not press them, even in the face of continuous reminders from the robot.

The experiments went as expected and highlighted the positive and negative features of the structure and the implementation of the movements.

6 | Conclusions

Investigating the domain of social robotics is an ongoing process, attempting to discover means to give life to mechanical forms of different levels of complexity.
During this study, we used concepts from different disciplines not strictly related to the field of automation to define an effective interaction through the movement of mechanical joints.
We aimed to create a robot that could relate to people on two levels. The first is strictly communicative, where the machine can collaborate with the user by transmitting directives and directions. And a second purely empathic level, in which the robot conveys its intentions, desires, and emotions to the people it interacts with.
This was achieved in the experimental phase, as demonstrated by the tests presented and confirmed by the participation of the people who interacted with Odile.
We managed to create a robot that was modular and reconfigurable. This allowed us to adapt it almost immediately to two different scenarios during the experiments, modifying almost exclusively the control of the robot and not its structure or movement programming.
The problems we encountered during the execution of the project can be divided between the implementation phases of the mechanical structure and the control.
To realize the different mechanical components, we immediately thought of mechanisms that could withstand the speed and fluidity of the movements without risking malfunctioning. This made the construction process long and caused a few problems during the programming and testing phases.
During the design phase of the movements and related control of the robot, we came up against the complexity of the structure. We implemented several methods to solve this problem by limiting the degrees of freedom without losing too much of the expressiveness and malleability of the configurations achievable by Odile.
We also tried to keep the control as simple as possible so that an inexperienced manipulator could quickly become familiar with the commands.

6.1. Future developments

Starting from the basis provided by this project, we can identify several lines of future developments.

The structure presented can be improved in terms of the direction of movement. This can be done by implementing a *PID* [37] control. This would allow the full potential of the base to be exploited, making the robot overall more responsive and easier to control.

The third module is designed to be responsive and solid against abrupt movements. It could be further improved in terms of its overall weight. A cleaner and more expressive movement could be achieved by using lighter materials and designing joints to limit the weight distributed on the arms.

One level of research is the expressive actions performed by the robot. When programming the gestures, we linked the movements of the motors proportionally in pairs, trying to maintain the robot's attitude but simplifying the commands. One aspect that can be improved concerns the quality of control. It would be interesting to study other movement configurations in which Odile can express itself by untying the motors and allowing the robot to move all body parts individually.

In general, the people who physically interacted with Odile during the second experiment realized that the caress they gave affected the robot. This feedback was provided by the robot's willingness to help the player find the correct buttons to exit the maze. An activity should be started to investigate about what kind of reaction is essential for the user to understand that the robot has been apprised of their activity. We still wonder whether the acknowledgment of the interaction can be activated solely by a movement or a more explicit signal is needed, such as a light or sound.

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