Design of a Small Swarming Robot Showing Intuitive Human Interaction

Integrated Product Design Report – 25/06/2025

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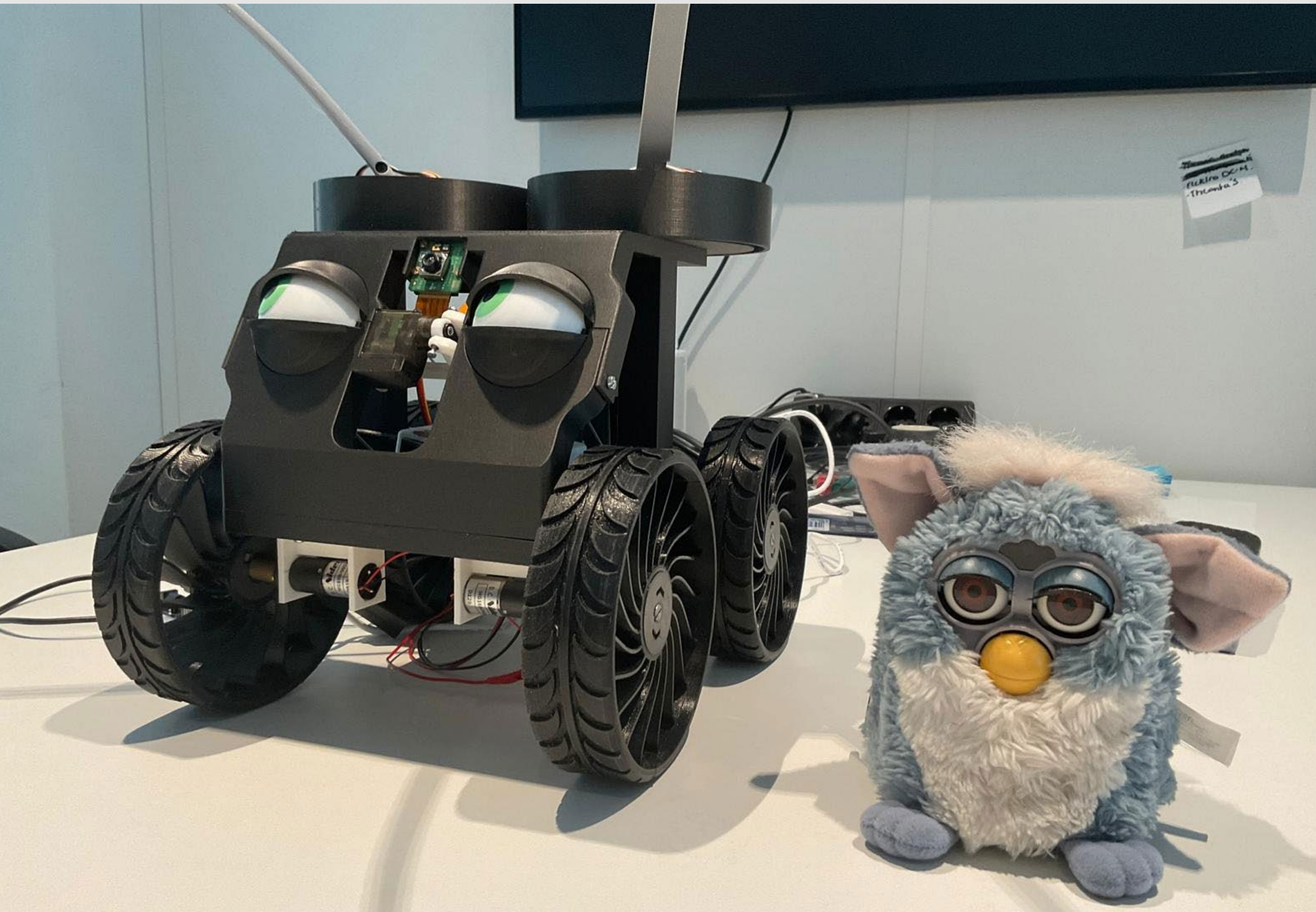

Preface

This thesis was written as part of the Embedded Systems and Integrated Product Design master's programs at Delft University of Technology. It reflects a personal interest in bio-inspired robotics, which was sparked during my time working with the Lunar Zebro team during my bachelor's.

I thoroughly enjoyed the process of rapid prototyping and appreciated the opportunity to combine academic research with hands-on experimentation. The project encouraged me to explore topics well outside my original field of expertise, including interaction design and the behavior of both humans and animals—subjects I have come to value as essential components in designing intuitive robotic systems. The process of this project highlights my favorite engineering quote: "Anyone can build a bridge that stands; it takes an engineer to build a bridge that barely stands". It takes an engineer to build a **precisely sufficient system.**

I want to express my deepest gratitude to my two supervisors, Dr.ir. C.J.M. Verhoeven and Dr. J.H. Boyle, for their support and encouragement throughout this journey. Your expertise and insights have been instrumental in shaping this work. I am especially thankful for your willingness to take on a long and complex project and for the personal input you provided throughout. I am glad we could find a topic that genuinely interested all three of us and that you were open to taking creative risks together.

I also wish to thank Dr. Marco Rozendaal for his thoughtful participation as a member of my graduation committee. His perspective and feedback, especially on the design and interaction elements during Human-Robot Interaction lab meetings, were greatly appreciated and added meaningful depth to this project.

I am also grateful to the Lunar Zebro team and the Mirte team for providing the robot and the technical foundation on which this project was built. Your innovative work made this project possible. Additionally, I sincerely thank the Human-Robot Interaction lab for their constructive input during the exploration and ideation phase. Your insights and feedback added a valuable dimension to the research.

To everyone who has supported me along the way - friends, family, and fellow students - thank you for your encouragement and patience throughout this process.

Aart Rozendaal

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Abbreviations

BID	Bio-Inspired Design
BoM	Bill of Materials
CSV	Comma-Separated Values
DUT	Delft University of Technology
ES	Embedded Systems
FLIP	Friendly Logic-based Interactive Presence
FPS	Frames per Second
FSM	Finite State Machine
HRI	Human-Robot Interaction
HSI	Human-Swarm Interaction
IPD	Integrated Product Design
LZ	Lunar Zebro
RP	Raspberry Pi
SR	Swarm Robotics

Abstract

This thesis explores the design and development of a bio-inspired robotic module that enhances intuitive human interaction within a swarm robotics context. The work addresses a research gap in Human-Swarm Interaction by focusing on how individual swarm robots can express emotions and respond to humans in meaningful, non-verbal ways, drawing inspiration from both domesticated animals, like dogs, and arthropods. The project integrates sensory and expressive components such as eyes, antennae, and body movement into a modular "symbiote" that can be mounted on existing robots. Through iterative prototyping, user studies, and expert consultations, the research identifies key emotional states and corresponding expressive behaviors, culminating in a module that communicates through movement of its appendages. The module supports real-time interaction and demonstrates the potential for robots to form more natural and intuitive relationships with human users, especially in exhibition environments like TU Delft's Cyber Zoo. The findings contribute to the fields of bio-inspired design, swarm robotics, and human-robot interaction by offering a novel approach to enhancing emotional legibility and engagement in robotic swarms.

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1 Introduction

Nature has been an incredible source of inspiration in the fields of Bio-Inspired Design (BID) and Bio-Inspired Robotics (Zhao, 2024). Animals, for example, have had billions of years to evolve many effective and efficient sensory organs, from which researchers and engineers can take inspiration. Besides the individual properties of sensory organs and organisms, the organizational structure of groups of animals has been shown to be an ever-intriguing topic of research. These groups of animals, in some cases, can be called a swarm. The definition of which will be discussed in this report.

Most people can intuitively grasp swarming as we see it in nature with flocks of birds, colonies of ants, hives of bees, and schools of fish (Yamaguchi, 2018). Without awareness of the system they are part of, the individuals can accomplish tasks exceeding their competencies. Studying these phenomena and their effects shows interesting results and uses in many fields. When implemented in the field of robotics, we will talk about Swarm Robotics (SR).

Within a robotics project, communication between humans and the robot is crucial, whether it is through speech, typing, lights, levers, buttons, or any other way of communication. The extent to which humans can understand the robot and vice versa is responsible for its effectiveness. This is why considerable advancements have been made in this field, e.g., Google Home voice recognition and human speech, ChatGPT with almost human responses, and UIX interface design improvements that make apps and websites more intuitive. Human Robot Interaction (HRI) is the scientific field that studies these interactions.

1.1 Motivation & Team

The research direction of this report is a combination of the research fields of BID, SRs, and HRI. This combination of these research areas, as shown in Figure 1, allows for an interesting and novel project that can tackle the knowledge gap for Human-Swarm interaction (HSI), which will be discussed later.

Furthermore, this research area also fits the interests and expertise of the student Aart Rozendaal and his graduation supervisors, Dr.ir. Chris Verhoeven and Dr. Jordan Boyle. Aart is studying embedded systems and integrated product design at DUT and is interested in combining hardware and software using BID. Dr. Boyle is part of the HRI group at DUT, which will be consulted during the project. Dr.ir. Verhoeven is the Project Director at Lunar Zebro, whose terrestrial robot will be used as a case study for this report.

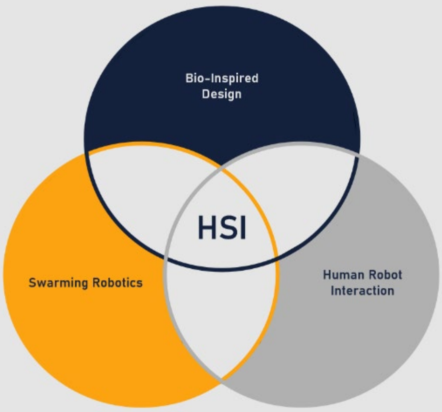

Figure 1: Venn diagram of the research area

1.2 Problem Definition

In 2014, the Cyber Zoo at the Science Centre on campus DUT opened (Delta, 2014). It opened to allow more research on robot swarms whilst also allowing visitors to interact with the robots. Since opening, the Cyber Zoo has been looking for innovative interactive robot designs and experiments.

The Lunar Zebro team has a terrestrial robot, Traici (Figure 2), which is used to test important systems of the version that will go to the moon. The design of Traici and the other Zebro robots resembles a beetle (Dutch: kever). It is a small six-legged robot consisting of relatively basic forms and features. Traici can already move, sit, stand, change stance, and do other basic locomotive tasks. Research in this report mainly focuses on how locomotion can help convey information.

In this report, the task is to create:

A robotic artifact to add to the Cyber Zoo that can interact with visitors as an add-on to Traici, Mirte, or any other (swarming) robot.

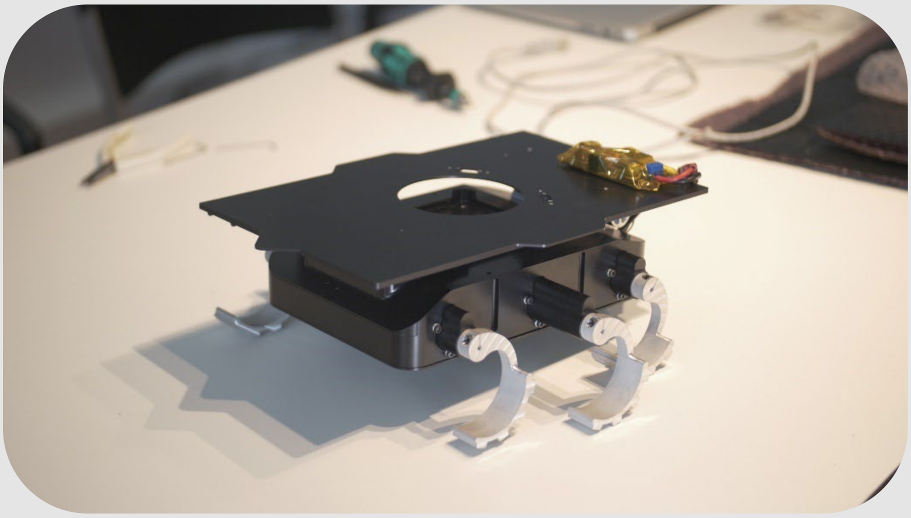

Figure 2 The current version of the Lunar Zebro robot (Traici)

1.3 Design Approach

The design process for this project will be iterative and dynamic. Using phases and milestones helps to track progress, while it allows for revisiting earlier assumptions and decisions. This non-linear approach allows each phase to build on the insights of the previous one, creating a continuous cycle of development and refinement.

In this methodology, key findings drive the process. Uncovering new opportunities or wrong assumptions earlier through rapid prototyping helps in faster progress at the cost of the project structure. Rapid prototyping, combined with an iterative methodology, ensures flexibility to adapt to unexpected challenges and use newly discovered opportunities. Rather than progressing in a straight line, the process loops back on itself. This approach is particularly beneficial in this experimental environment, which will require a lot of testing.

1.4 Report Structure

Although rapid prototyping and iterative design can lead to a chaotic structure, this report follows a predefined framework. When later findings change earlier concepts, they will be revisited and changed. This means that the findings mentioned in the report might not be in chronological order. When something is not in chronological order, it will be mentioned.

The report will consist of several phases with corresponding chapters. The structure is as follows:

- Phase 1: Literature review, vision, and scope
- Phase 2: Exploration, Ideation, and Conceptualization
- Phase 3: Technical design, interaction design, and analyses
- Phase 4: Testing and validation
- Phase 5: Challenges, Conclusion, and Future Work

Below, in Figure 3 the double diamond shows the progress and report structure schematically.

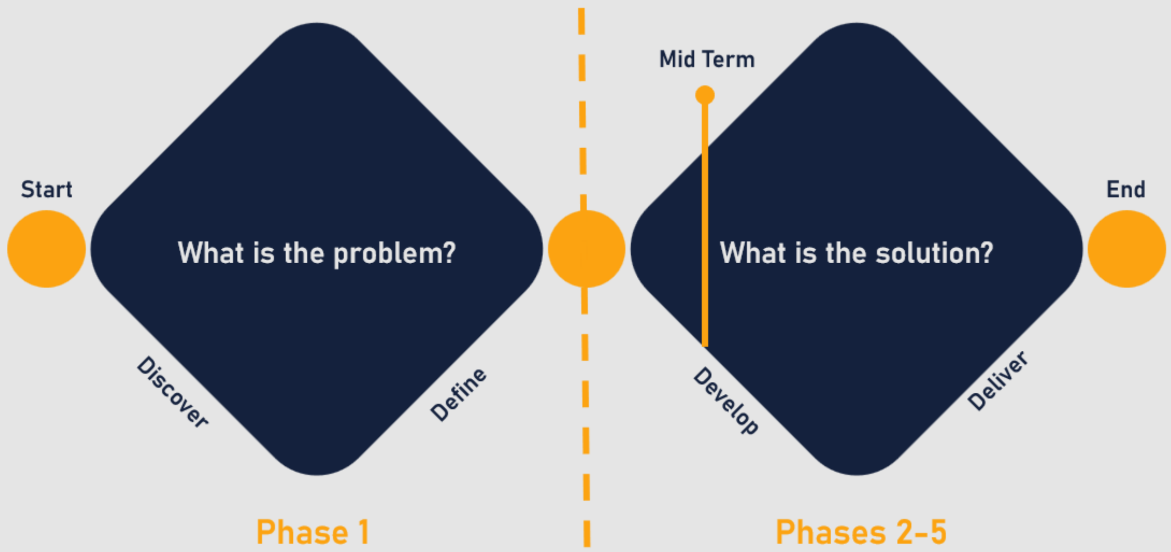

Figure 3 Double diamond structure used for the report, phase 1 contains discovery and definition, and phases 2-5 contain development and delivery.

1.5 Planning

The project followed the phases mentioned in the previous section. During these phases, several meetings took place between the graduating student and the supervisors. Furthermore, several sessions with the HRI lab helped during the project. A detailed overview of the overall planning is shown in Figure 4.

Figure 4 Planning of the project showing the Phases (Blue), the chapters (Orange), and the weeks with corresponding meetings and events (grey, with important meetings in dark grey)

2 Literature Review

This chapter takes a look at swarming and connects it to robotic swarms. We will construct our own definition of swarms based on previous papers and definitions. After that, we will look into communication, human-animal interaction, human-robot interaction, and human-swarm interaction.

2.1 Swarming

To gain a better understanding of swarm robotics, it is helpful to start by defining what a swarm is. We begin by looking at a very general definition of swarming and start from there. We remove elements, change words, and take parts from different definitions. This way, we can create a definition for swarming that is complete and relevant for this work. After that, we can use this definition as a starting point for looking at robotic swarming.

2.1.1 Definitions of Swarming

A Swarm is defined in the Merriam-Webster dictionary as: “a large number of animate or inanimate things massed together and usually in motion” (Merriam-Webster, 2024a). Which already mentions some important criteria.

Let us start with it should be “a large number”. A large number is difficult to define but can often be intuitively grasped. There is no definitive number starting from which we would say: “This is a swarm.” This implies some subjectivity to the term Swarm. In nature, swarms often occur in large groups, and further defining this number would not be useful.

The second point, “animate or inanimate”, tells us that the “thing” can be something that is not alive. Using the definition of animate: “Possessing or characterized by life” (Merriam-Webster, 2024b), this paves the way for robots to also form a swarm.

The criteria of “usually in motion” creates a certain level of ambiguity. In this definition, a forest full of trees would qualify as a swarm as it is a large group of animate objects that are in motion, due to winds, rain, and other external factors. However, this is not a form of motion that originates from the “thing” itself. Classifying a forest as a swarm would be neither practical nor clarifying what a swarm is. It makes more sense to describe the “thing” as something actively participating, and the way it participates involves motion. Thus, we can change “thing” into “agent” and “usually in motion” into “mobile”.

To discuss the criteria of “massed together,” we will use another definition. This definition is: “A large group of locally interacting individuals with common goals” (Barca, 2013, p. 1). This definition implies that individuals in a swarm must interact with one another, which is missing from the first definition and arguably crucial. Therefore, it would be helpful to add some form of communication or interaction to our definition. Here, we can also give more context to these two terms. “Massed together” and “locally interacting” imply a certain proximity. For bees that communicate through intricate dances and use pheromones, this could be several centimeters and several meters respectively (Barth, 2005). Later, when we connect this to robots that can use radio waves for communication, we can see that these distances change. Because proximity is not essential for communication and the behavior of the swarm, we can rewrite it. Combining what we just said, we could use: “capable of peer-to-peer communication”. This peer-to-peer communication can be direct or indirect. Direct communication methods in nature are more well-known and include pheromones and visual and auditory methods. Indirect methods are less well-known. This mechanism is called

Stigmergy, where the environment is used as a method of communication (Duan, 2012). Pheromones can also be used as an indirect communication method. The way swarms communicate is also relevant to some characteristics, like decentralization, which we will discuss later.

Another criterion, which was also missing from the first definition, is that of a common goal. Let us discuss this in more detail. Most swarms (in nature) consist of relatively simple individuals that solve complex problems that exceed their individual capabilities. Solving these problems is their common goal, even if they are not aware of the common goal. For example, no single bee can build a hive, but together they exceed their capabilities and achieve this common goal. Even the bees that are just getting nectar from the flowers to feed the builder bees are working towards the creation of the hive, without knowing or directly contributing. However, even just survival in a swarm can be seen as a common goal. For example, a school of fish can only survive when working together and having survival and reproduction as their common goal. Without a common goal, there would just be many individuals close to each other.

The last criterion we will touch upon is more debated. Arguably, the definition of a swarm could contain the condition that the swarm should be homogeneous. This discussion is even more relevant when talking about robotic swarms later on, as in nature it often seems to be the default – that is, homogeneity. However, a swarm of bees contains worker bees and drone bees that have a common goal but are not a homogeneous group (Rutter, 2022). If homogeneity is part of the definition, then that would mean they are two different swarms. The swarm consists of individuals that are part of multiple homogeneous sub-groups. I would argue that this is still one swarm with one goal, but it has individuals with different tasks, even when individuals are physically different. To accommodate for this in the definition, we will add that the group is “quasi-homogeneous”.

Here, **Quasi-homogeneous** refers to a group composed of individuals that are not entirely identical in form or function but share enough similarities in behavior, capabilities, or objectives to be treated as a cohesive unit. In the context of swarms, this term allows for limited variation among agents, such as differing roles or physical features, while preserving the collective identity and coordinated function of the swarm.

2.1.2 Our Definition of Swarming

Combining everything that was mentioned above, our definition of a “swarm” would be:

“A Large number of animate or inanimate mobile agents in quasi-homogeneous groups with a common goal, capable of peer-to-peer communication”

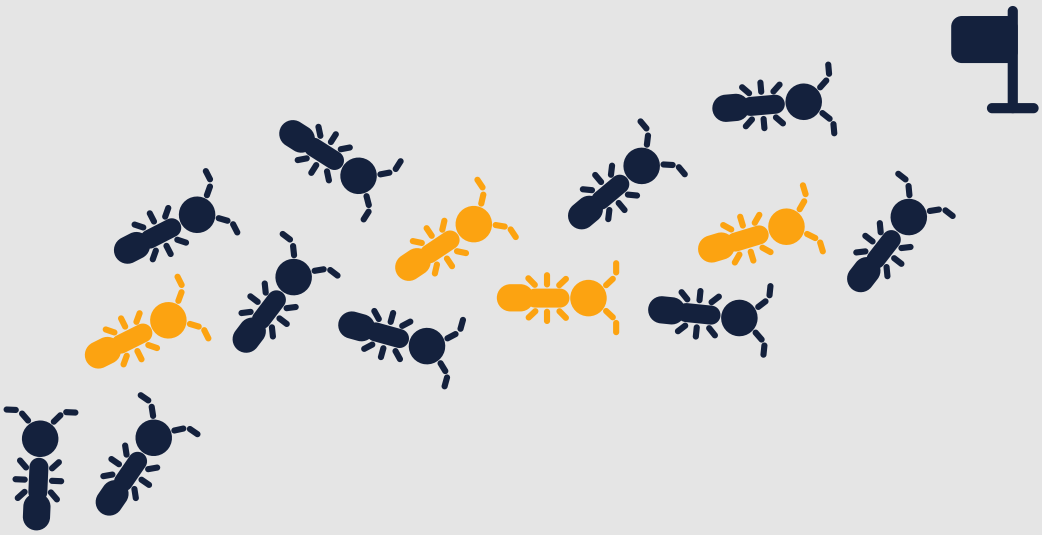

Figure 5 Visual representation of a swarm, showing a large number of animate agents capable of communication (ants) that are orange and blue (Quasi-homogeneous) working towards a goal.

Later, when talking about robotic swarms, we can further define this statement and discuss it in a relevant context. Besides a definition of a swarm, it is also helpful to talk about general observable properties and characteristics of swarms. These make studying them interesting and valuable. These will also be organized and restructured later when talking about robot swarms.

2.1.3 Observations About Swarms

Decentralized Control: Because swarms can only communicate locally (or peer-to-peer), there is no way to ensure global knowledge. This means there is no real centralized control. This can both be seen as an advantage and a disadvantage, but it does require the agents to act autonomously, which organisms in nature usually do. All individuals respond to sensory inputs in a relatively simple way and use information from their peers to alter their behavior (Brooks, 1999). By constantly communicating with their peers, they can work together on a common goal without any individual grasping the full scope of this goal.

Scalability/Robustness: Because of the (quasi) homogeneity and decentralization, swarms are often highly adaptable and robust (Pugh, 2009). Individuals can die (or break down), get lost, malfunction, or be removed while the rest of the swarm can continue. Losing an individual in a tribe, herd, or even a company where individuals function hierarchically often has significant consequences. This also works the other way around. Increasing the number of agents in the swarm is easy. Each agent is autonomous, and the decentralized control scales well.

Emergent behavior/Swarming intelligence (Beni, 2005): This stems from theories of reactive intelligence that apply to swarms. Through the simple behaviors of many individual entities, intelligence emerges in the swarm as a whole (Kennedy, 2001). Even without communication, when robots (or any agents for that matter) react simply to only sensor inputs, complex behavior can emerge (Brooks, 1999). This is especially true for swarms in nature, which have had millions of years to create fully functional autonomous agents with efficient peer-to-peer communication. Swarm intelligence and emergent behavior are fascinating and are key drivers of swarm research.

2.2 Swarming in Robotics

The observations and characteristics mentioned in the previous chapter make research into robotic swarms interesting to solve issues that cannot be easily solved by other means. When creating a robot that needs to complete a complex task, both software and hardware can become complex and expensive. Nature shows an incredible solution for this issue in the form of swarms.

Before talking about the advantages, challenges, and use cases of robotic swarms, let us adapt and refine our definition.

2.2.1 Definitions of Robotic Swarming

Let us start with the most obvious alteration: we change "animate or inanimate mobile agent" into "mobile robot". We still want to keep "mobile" in there, as we would not consider a sensor array or assembly line as a swarm. Active movement remains a requirement for a swarm.

When talking about the common goal, we can add that working towards this goal should be done cooperatively. In robotics, this should be explicitly mentioned (Arnold, 2020; Tan, 2013). If it is not stated, then a group of robots performing tasks independently but communicating would be considered a swarm. This would not allow for any interesting observations. These robots would not show emerging behavior and would not be useful in the context of this project.

In another paper, a robot swarm is defined as: "an approach to the coordination of multiple robots as a system which consists of large numbers of mostly simple physical robots" (Liu, 2000). This contains many criteria we have already discussed, but touches upon a new one. It states that it should consist of simple robots. However, today swarms can also consist of more complicated individuals. Complicated individuals can also show emergent intelligence and swarming behavior. In our definition, we will leave out this discrimination as it is less relevant.

This definition also mentions that a large number of individuals are required. It is helpful to rephrase this statement for robotics because a swarm of ten more complicated individuals could be considered a swarm and show all characteristics. This begs the question: should it be a large number of robots, or should they merely be made to facilitate the possibility of expanding the number of robots, as scalability is an important characteristic? Much research is performed on smaller swarms with scalable efforts, showing swarming capabilities (Arnold, 2019; Kopeikin, 2019). In recent work, a robotic swarm is defined as: "A group of three or more robots that perform tasks cooperatively while receiving limited or no control from human operators." In (Arnold, 2020). Assigning the number three feels arbitrary and does not necessarily help with the explanation of a swarm. Therefore, we will abstract from numbers and use the word "Multiple".

Arnold further defines his statement in his work. On limited control, he has the following description: "The swarm as a whole is controlled by either zero or just one human-operated control station. This control station does not control the specific movements of each member of the swarm; rather, it controls broad behaviors and objectives of the swarm as a whole." (Arnold, 2020).

The statement on limited control is interesting and ties into the fact that every robot should function autonomously. In the general definition of swarming, this is also implied, as in nature, organisms always function in this way. For robots, it should be explicitly mentioned that this is the case. The autonomous behavior of the robots implies that there is limited control. Meaning we can leave it out of the definition.

2.2.2 Our Definition of a Robotic Swarm

Combining everything, we have a new definition for swarm robotics. The definition of a robotic swarm is:

> **"Multiple autonomous mobile robots working cooperatively on a common goal aided by communication"**

Let us go over this definition bit by bit;

Multiple: Abstracting from a specific minimal number. We need enough robots to show the characteristics of a swarm. However, a robot can be a swarm robot without functioning in a swarm when it is designed to be able to do so.

Autonomous: Each robot in the swarm should function by itself. It should prioritize its own survival and critical tasks over group activities.

Mobile robots: Each robot in the swarm should be able to move. This can be done in any way that actively performs this task without external forces, e.g., wind. This excludes sensor arrays and assembly lines from the definition of a swarm. A swarm could contain robots that are not able to move on their own but require help from others. However, they cannot exist solely out of non-mobile robots.

Working cooperatively: The robots should work together in a symbiotic manner, i.e., helping each other in achieving the common goal. Otherwise, they are merely similar robots working on the same task.

On a common goal: The robots should have a common goal that they can work cooperatively on. The simple goals could be survival or interaction with the environment. Without a common goal, it would be similar robots doing different things.

Using communication: The communication between the robots often happens peer-to-peer, meaning that they use local communication and cannot guarantee global information distribution. Communication can be in many forms, ranging from speech, radio, and light to using Stigmergy.

2.2.3 Key Properties

Before continuing, we need to address three key properties that most robot swarms exhibit. The reason for not including these in the definition is that they are arguably not essential. Of course, opinions on this may vary through the literature. They are mentioned because these properties are often present in swarms, and they can be responsible for interesting behavioral concepts. The behavioral concepts that stem from these properties are called attributes.

Decentralized Control

The first one we already touched upon. Most swarms use decentralized control. In some definitions, it is also described that swarms have "limited control" or "little human intervention". Having decentralized control with autonomous agents allows for emergent behavior to appear. In swarms, this can express itself as swarm intelligence.

Homogeneity

Secondly, most swarms are (quasi-)homogeneous. Swarms can be non-homogeneous, but this does negate some of their most valuable attributes. Homogeneity, paired with decentralized control, can allow for a robust and scalable system. Both are attributes that researchers are keen to learn more about. Robustness is a system's ability to remain functioning under disturbances (Mens, 2011). In the context of swarms, this would be losing individuals, for example. Scalability is the ability of a system, network, or process to handle a growing amount of work capably or its ability to be enlarged to accommodate that growth (Norman, 2012). In our context, this would mean adding individuals to the swarm.

Common Memory

Lastly, most swarms can have a common memory. Although in nature, individuals in a swarm may not know the goal and the state of all other individuals, for robots, this is easier to achieve. This stems from robots' ability to communicate reliably, quickly, and over large areas, whilst also allowing for more reliable and larger memory storage than any animal. Besides that, cloud technologies and satellites can provide common memory and measurements for all robots. **This allows for an attribute that is not seen in nature – morphic resonance**. This term was originally coined by Rupert Sheldrake (1981) in his book A New Science of Life: The Hypothesis of Morphic Resonance. It describes a form of biological growth through a common memory shared through morphic fields. Although it was described as pseudo-science, it now seems to find its application in the field of swarm robotics. In short, it is an attribute that allows swarms to grow and improve through sharing observations over morphic fields, e.g., radio waves, and harboring common memory.

Below in Figure 6 It is a hierarchical overview with the definition, the three key properties, and the attributes that those properties lead to.

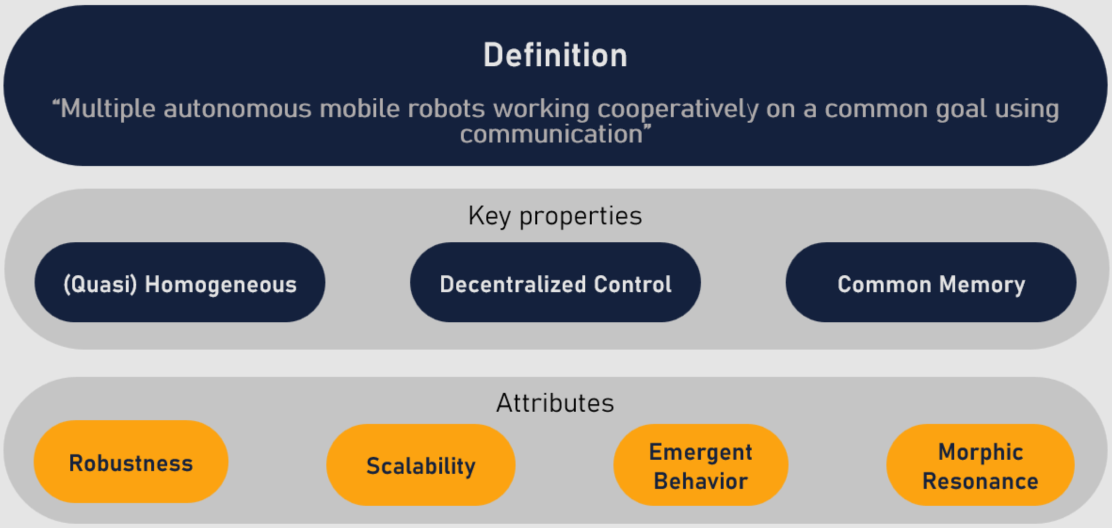

Figure 6 Hierarchical overview of the definition, properties, and attributes of swarms

2.2.4 Advantages

As opposed to robots that function in swarms, they can have many. A non-exhaustive list is given below:

Replaceable and Low Cost

Low cost, homogeneity, and decentralized control make robots in a swarm highly replaceable (Arnold, 2020). Perfect for dirty, dangerous, and tedious situations. The replaceability of the individual robots makes a swarm as a whole a very robust system (Pugh, 2009).

Awareness and Response Time

The individual robots act autonomously and can quickly respond to changing situations. These autonomous individuals can also spread out over a larger area, outperforming both humans and individual robots. Furthermore, robot swarms can exploit the sensory capabilities of the group (Barca, 2013). This also helps with finding any area of interest quickly (Vincent, 2004). This further increases response time and provides an overall better situational awareness (Edwards, 2000).

Simpler Design

Simple robots can solve complex problems when working together (Arnold, 2020): Due to emergent behavior and swarm intelligence, simple robots can solve a complex problem together. The robots can distribute work over a larger spatial area and multiple individuals (Uny Cao, 1997). They can manipulate the environment more efficiently, attack a problem from multiple angles, and carry out multiple tasks simultaneously (Barca, 2008). Making swarms better at solving specific problems than some traditional robots.

Fewer Human Interactions

Because of the decentralized control and the fact that the robots can function autonomously, fewer or no human operators are necessary (Arnold, 2020). This saves on personnel costs and training time. Furthermore, swarms can be used in dangerous situations – mine removal, search and rescue, and wildfire monitoring – and replace humans, preventing unnecessary risks (Barca, 2008).

2.2.5 Challenges

Besides many benefits, swarming technologies are still facing difficulties and challenges. Much literature is available on this, and many of these challenges are actively researched. Again, a non-exhaustive list is given below:

Complicated Control

Creating a robust system where individuals are replaceable and they can adapt to changes in the environment requires decentralized control. Because of this, it is challenging to ensure global data. This makes it difficult or impossible to ensure that all individuals are working on the same objective or goal effectively. This presents one of the most significant issues – the predictability of the behavior of the swarm (Barca, 2013). This can create systems that are susceptible to erratic and unpredictable behavior.

Swarm Formation

Creating a framework to address a specific problem is difficult without global data and with decentralized control. Formation, generation, and maintenance require connectivity and information sharing (Donkoh, 2024). Depending on the formation method and the data sharing method, this can have a significant impact on energy efficiency (Kernbach, 2011).

Energy Management

Each individual in the swarm acts autonomously, meaning it is responsible for its own energy level. Charging one robot can be done in many ways, but charging several to thousands of robots creates a new challenge. It narrows down solutions to only a few possibilities (Seyfried, 2005). The energy consumption of these robots can collectively be much larger than that of individual robots. Without a sufficient energy source, the whole swarm could stop working (Anderson, 2003).

Hardware

Components that are available at the time of production might not be available a few months later. The design of a swarm needs to account for possible slight changes in the near future. Besides that, different missions might require different hardware, which would require a new swarm, something that is a smaller issue with individual robots (Arnold, 2019).

2.2.6 Communication

Because the second focus point of this report is on interaction, we will take some extra time to look at communication. This includes both communication between robots and between robots and humans. Later, we will mainly focus on the latter.

One of the most significant advantages of robotic swarms over biological swarms is their communication efficiency between individuals. **Robots can communicate more information with fewer mistakes over longer ranges**. Communication can be done in different ways (Frater, 2006). Often, direct forms of communication are used, but indirect methods – like Stigmergy – are also possible (Duan, 2012). In Table 1 We discuss some of the communication possibilities for swarms and mention a biological equivalent or inspirational source:

Table 1 Examples of communicative media in robot swarms, with their properties, and examples of similar communication methods in nature

Type of communication	Properties	Inspiration from biology
Electromagnetic signals or fields – like Wi-Fi, Bluetooth, and radio (Frater, 2006)	- High data rate - Reliable - Long range - interference and bandwidth limitations in larger swarms	Elasmobranch fish avoid predators and catch prey (Kalmijn, 2000)
Stigmergy, i.e., changing the environment to convey information (Duan, 2012)	- Low complexity - Scalable - limited information - Slower - Messages can be erased	Ants use pheromones to leave trails for others (Dorigo, 2000)
Visual communication by using LEDs (Frater, 2006)	- Low power consumption - Low complexity - Depends on lighting conditions - Requires line of sight	Fireflies use lights and dances to communicate with each other (Baral, 2022)
Infrared (IR) (Trenkwalder, 2020)	- Low power consumption - Low complexity - Depends on lighting conditions - Requires line of sight	Snakes can detect prey and others using infrared organs (Kever, 2020)
Sounds in both the audible and	- Does not require line of sight - Can be made audible or not	Birds use sounds (Podos, 2022) and dolphins use

inaudible spectrum (Frater, 2006)	- Slower - Prone to interference from the environment	ultrasounds (Ridgway, 2009) to communicate.
Tactile or vibration – could not find an example in a swarm yet	- Works in any environment - No interference at short range - Low power consumption - Only short-range communication - Limited data transfer - Requires touch	Spiders can detect entities through vibrations (Mortimer, 2019)
Chemical markers – could not find an example in a swarm yet	- Works in dark and noisy environments - Persistent over time - Difficult to control duration and target - Limited in windy environments	Pheromones are chemical markers left by ants (Dorigo, 2000)

2.2.7 Uses of Swarms

Robotics technology is becoming cheaper and more capable at an increasingly rapid pace, expanding the feasibility of deploying robots as solutions to situations ranging from disaster recovery to mapping to reconnaissance (Arnold, 2020). The potential for swarms is huge. Some examples are (Olaronke, 2020):

- Mining
- Military
- Medical
- Agricultural
- Search and rescue
- Toxic waste cleanup
- Disaster prevention or cleanup

Currently, most tests and progress in these areas are relatively immature or only in the simulation phase (Arnold, 2019; Ramchurn, 2016). Nevertheless, swarming has shown to be a promising solution for these issues that traditional robots struggle to help with. In short, swarm robots could help in sectors that are:

- Dangerous for humans and robots, as robustness and lower cost mean losing individuals is a less severe issue;
- Require upscaling and downscaling of robotic teams;
- Require large coverage, omnipresent, or parallelism;
- Prone to having issues that require adaptive or unknown solutions;
- Or are too complex for one robot.

Furthermore, the fact that swarms show emerging behavior and morphic resonance could lead to discoveries and inventions.

2.2.8 Knowledge Gap

One more interesting application of swarms is not often mentioned in the literature. **Swarms can be used to test and study behaviors that are present in nature**. Swarming intelligence is well-known but not well-understood. Using swarms of robots, even without real-life "useful" tasks and goals, can be used to study these behaviors. Furthermore, they can be used to study human-robot interactions in a setting different from the one-on-one interactions that are more common.

2.3 Human-Robot Interaction

To learn more about HRI, especially when using BID, it is interesting to study human-animal interaction first because we can take a lot of inspiration from nature.

2.3.1 Human-Animal Interaction

Interactions between humans and animals rely on centuries of coexistence, evolution, and shared experience (Nyhus, 2016). The first interactions were mainly for defense and food, and that is why humans were responsible for the extinction of many large mammals during the Pleistocene (Surovell, 2015). The earliest signs of humans more closely interacting with animals are visible in cave paintings (Guthrie, 2005). Here started the first real behavioural adaptations in humans and animals towards each other. Later, in texts from ancient Egypt, Greece, the Roman Empire, and the Bible, interactions showed more symbiotic relationships

(Conover, 2001). This co-evolution turned into animals getting better at communicating with humans through the recognition of human cues. Here we discuss these topics and the effects these interactions have on people.

The ability of animals to change due to human presence shows in two ways: evolutionary changes that can be mainly seen in species that reproduce fast, and behavioral changes in species that reproduce more slowly (Gruber, 2019). The latter is more interesting as it shows genuine behavioral adaptation within the animal as opposed to slow evolutionary shifts in species, which can be influenced through human intervention, i.e., breeding. For these – often larger – slowly reproducing species, behavioral change and flexibility are the main (or only) way to respond to environmental changes (Schuppli, 2016). Below, we will discuss some of the major adaptation categories. These categories go from avoiding and opposing humans to tolerating and domesticating.

Behavioral change due to human threats and conflicts

With humans taking up ever more space and shrinking animal habitats, we are forcing these animals to change their behavior quickly. Chimpanzees show fear for humans (Tucker, 2018) and actively avoid them, whilst elephants change migration behavior because of destructive human activities (Bates, 2007). Animals like elephants can also remember negative actions performed by humans throughout their lives and teach their children to avoid them or act more aggressively (Moussaieff, 2009). This aggression is more evident when competition for resources or territories arises. Wolves are increasingly attacking livestock in the Netherlands and Germany because there is less wildlife (WWF, 2024).

Tameness and reduced fear of humans

When animals are “useful” or do not have to compete with humans for resources, they can often coexist. Here we see that they often develop reduced fear of humans. Often, more non-threatening contact with humans can reduce fear and create tameness in rabbits (Csatádi, 2005), chicks (Jones, 1993), and cows (Lürzel, 2016). We see this in farm animals, animals in parks, urban forests, and even in cities with doves. This is an adaptive strategy that reduces stress and sometimes even benefits them because they can start using human resources.

Urbanization of wild animals and use of human resources

With urbanization ever-increasing and massive metropolitan areas now spanning many square kilometers, animals have adapted to these human habitats. They start using resources like: human food with seagulls, pigeons, and bears (Spelt, 2021), shelter with rats, insects, and birds(Blasdell, 2022), and tools (crows).

Mimicry of human sounds and human-associated sounds

Some animals can now mimic human sounds and human-associated sounds like alarms, machine noises, and other mechanical sounds. This can be used to get closer to humans or obtain food from them. Other animals also mimic or read human emotions to get closer. This includes dogs using their bodies and facial expressions (Chopik, 2019).

Domestication and symbiotic relationships

Animals like dogs, cats, and bees often adapt their behaviour in response to human actions. Cats, for example, vocalize in unique ways to communicate with humans, while bees react to human pheromones. Dogs could be considered one of the most domesticated animal species and are often called “man’s best friend”.

Impact of these Interactions

Many animals, like dogs, sheep, and pigeons, can recognize human facial expressions, gestures, and even voice tones. They form bonds with humans based on these interactions (Chopik, 2019).

Humans have developed beneficial relationships with animals over time, such as with pigeons (for message delivery), sheep (for wool and livestock), and bees (for pollination). These relationships are often built on a shared understanding or mutual benefit.

These bonds can have a significant impact on humans, especially in the context of pet ownership, therapy, and farming. These dynamics have changed families, emotional well-being, and human social interactions (Serpell, 1991). Pet ownership can have significant physical and mental health benefits. This can even go as far as animals having religious status and providing religious relief (Gorlinski, 2018).

The use of trained animals in therapeutic settings to improve mental, emotional, or physical health. This includes therapy with dogs, horses, cats, and even dolphins. Therapy animals help with conditions like PTSD, autism, or depression, and the psychological mechanisms behind them (Gee, 2021).

2.3.2 Human Single-robot interaction

The study of human-robot interactions is very broad, and many studies either focus on parts of it or categorize it into several categories. For example, Sheridan (2016):

1. Human supervisory control of robots in the performance of routine tasks;
2. Remote control of space, airborne, terrestrial, and undersea vehicles for non-routine tasks in hazardous or inaccessible environments;
3. Automated vehicles in which a human is a passenger, including automated highway and rail vehicles and commercial aircraft;
4. Human-robot social interaction, including robot devices to provide entertainment, teaching, comfort, and assistance for children and the elderly, autistic, and disabled persons.

Because of time restraints and relevancy, I will focus mainly on the latter. This is also the category in which we can focus more on emotions rather than informational communication.

Interactions with inanimate objects

In the realm of social interactions between humans and robots, we can already focus on bio-inspired features. As discussed earlier, these have evolved over many millions of years. However, that does not mean humans are less likely to form bonds and relationships with inanimate objects, even when not similar to animals.

Forming Relationships with Inanimate Objects

Forming relationships with inanimate objects is often attributed to addressing the unmet needs of people (Wan, 2021). Anthropomorphizing objects can help with self-identity, self-efficacy, and a sense of comfort. This can go from giving names to objects to having full emotional connections. Three reasons for this kind of behaviour are:

Emotional Projection: People often project their own emotions onto these objects, creating a sense of relationship that reflects their own needs, thoughts, or feelings.

The desire for Connection: For those who are isolated or lonely, these objects can fulfil a need for companionship, providing a "safe" connection where they can express emotions freely.

Innate Human Tendency for Narrative: Humans have a deep need to create stories and relationships, even with objects that can barely reciprocate. This storytelling urge can make even a Roomba vacuum seem like a brave little companion on a mission.

Through these interactions, inanimate objects often become symbols or companions for their owners.

Examples of Relationships with Inanimate Objects

To better look at different levels of relationships with inanimate objects, we will look at several examples. Starting with interactions with objects least resembling animate things and building up to interactions with things that get closer and closer to living organisms, as shown in Figure 7 .

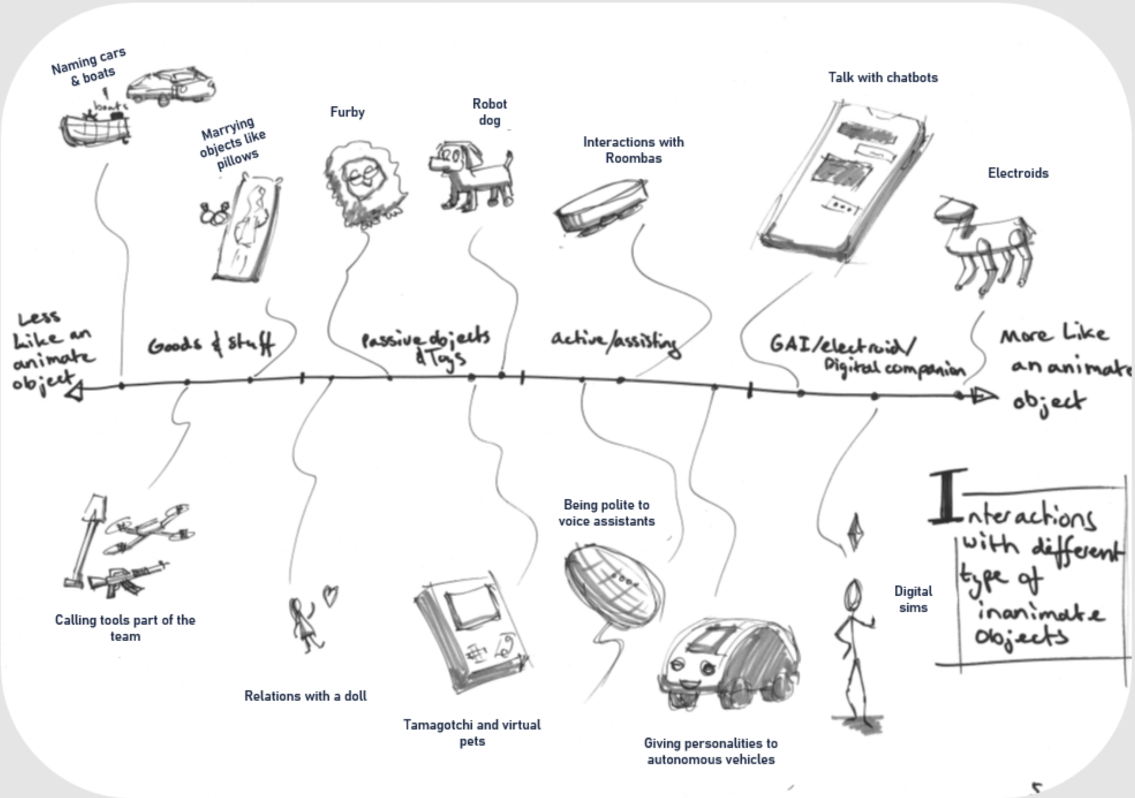

Figure 7 Relationships and interactions with inanimate objects, going from least resembling animate things (left) to most resembling animate things (right)

Personal goods

- People naming cars and boats, which leads to them having an increased attachment to them.
- Remote-controlled drones or weapons in military teams that are called "part of the team".
- People having intimate relationships with a body pillow.

Toys and passive objects

- Dolls are given names and played with. Often, children, but also adults, can give personalities to these dolls and have conversations.

- The Aibo robotic dog and Paro the robotic seal are examples of toy animals with minimal movement that are designed to create a relationship and bond with their owners.
- Furby is a non-existent creature showing several bio-inspired features.
- Tamagochi and other virtual pets allow people to create a relationship with a non-physical animal.

Assisting robots

- Alexa and Google Home have voices that sound almost indistinguishable from human voices. Here we see that people often say “thank you” or “excuse me” even though it is not necessary. Showing anthropomorphism.
- Roombas and other automated household robots are often given names and personalities. In some cases, people ask them to “do their job”.
- Autonomous vehicles having a ‘personality’.

AI, digital companions, and autonomous robots

- Talking to AI in a friendly way. Snapchat even went as far as creating an AI friend with whom all its users can have friendly conversations.
- People can get very sad when their video game character or virtual sim dies or gets hurt. Showing compassion and the feeling of growing a strong bond over an extended period.
- Boston Dynamics’ SPOT can have people treat it as a dog, and even have dogs treat it as a sheep.

Uncanny valley

The uncanny valley is a concept in robotics and computer graphics that describes the discomfort or eerie feeling people experience when encountering humanoid robots or digital characters that look almost, but not quite, human (Mori, 2017).

The idea is that as a robot or character becomes more humanlike, people’s emotional responses become more positive, up to a point. When the resemblance becomes very close but not perfect, the slight imperfections stand out and create a sense of unease or revulsion. This "valley" represents the dip in emotional comfort before the response becomes positive again, with perfectly human-like appearances. A graph showing this phenomenon is shown in Figure 8.

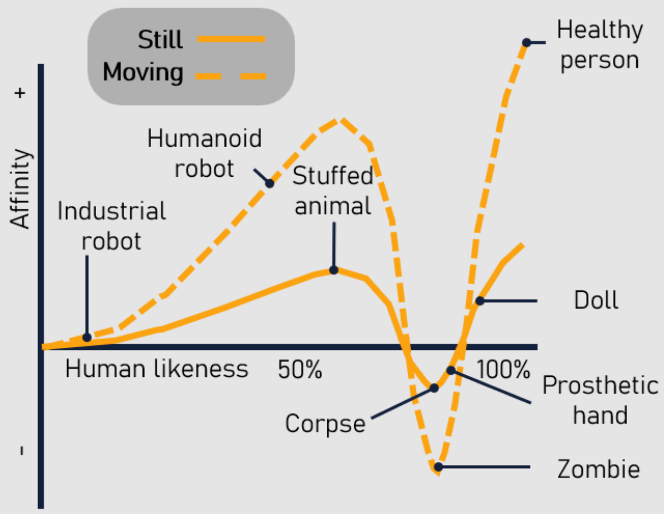

Figure 8: Graph showing the uncanny valley phenomenon with affinity towards an inanimate object against its likeness to humans (Mori, 2017)

Relationships with Animate and Inanimate Things: Comparison

Humans tend to form emotional bonds and attachments with animate and inanimate entities. People often assign names and project personalities and feel emotions like affection, empathy, or protectiveness toward robots, interactive toys, or devices. As mentioned before, owners of robotic vacuum cleaners like Roomba or robot pets like AIBO name them, talk to them, and even feel responsible for their well-being, mirroring the connections they might form with pets or humans. Roomba is adding a feature where you can talk to your device (IRobot, 2024).

Both animate and inanimate companions can provide a sense of companionship, helping to alleviate loneliness (Gee, 2021). Social robots like Pepper or AI-based apps like Replika are popular among individuals seeking comfort, offering interaction that mimics human conversation (Whitty, 2016). Many users report feeling less lonely after engaging with these AI entities, similar to the emotional comfort gained from speaking with a friend, but there are serious ethical issues.

However, there are notable differences in how people interact with animate versus inanimate companions. Living beings like pets or humans offer rich, unpredictable responses and genuine emotions, deepening relationships over time. In contrast, robots and AI-based companions can only simulate responses and growth within programmed limits. Relationships with animate beings evolve organically, while interactions with robots remain fundamentally asymmetrical and lack true emotional reciprocity, at least with current technologies.

While robots and digital companions offer benefits like predictability, availability, and reduced emotional risk, they also have limitations. Their lack of genuine emotion and mutual understanding may leave users feeling unfulfilled. Over-reliance on these entities can discourage real-world social interactions, leading to isolation and detachment. Additionally, projecting emotional needs onto inanimate companions may result in frustration when they fail to meet human expectations, raising ethical concerns about dependency and desensitization to meaningful human relationships.

Although relationships with inanimate objects are fundamentally different from those with living organisms, they do provide a vehicle for exploring new interactions. We live in a digital world, with people spending more than four hours in front of screens every day in the Netherlands (CBS, 2019). Researching interactions between humans and animals can help improve other interactions with computers, robots, and more.

2.3.4 Human-Swarm Interaction

Looking further into interactions between humans and robotic swarms, we see that scientific research is lacking, making this an exciting research topic. Previous studies mainly show research using simulated robots or lacking physical prototypes to test the interactions. We find research for simulations (Kapellmann-Zafra, 2016) (Kerman, 2012), a proposal (Naghsh, 2008), a survey (Kolling, 2016), or a focus on control interaction without a focus on the social interactions (Pendleton, 2013). The closest we get to studying social interactions is a paper by Alonso-Mora on giving gestures to swarms to control them (2015). This touches upon interpretation and a form of communication between a swarm and a human.

3 Vision and Scope

The literature clearly shows interesting research opportunities. Especially in the area of human-swarm interaction. With existing knowledge gaps and obvious potential benefits.

3.1 Context

It is important to provide context for this report within this research area. This report is written as a graduation report at the Delft University of Technology. As mentioned, one of the supervisors, Dr. Chris Verhoeven, is the project lead at Lunar Zebro. This is the reason for using their robots as inspiration. The location of the Science Center on the DUT terrain is also due to Dr. Verhoeven's connections. The Cyber Zoo is the perfect environment and case study for this report. Given this location and the Lunar Zebro robots, a context map was created as shown in Figure 9.

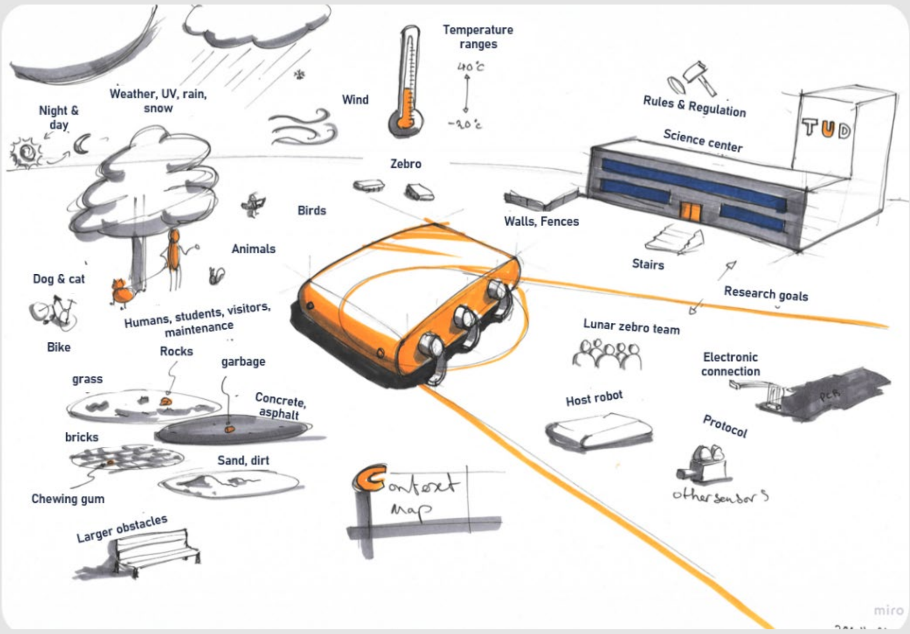

Figure 9 Context map for the project showing environmental, interaction, physical, and regulatory context

3.2 Stakeholder Analysis

Within this context, it is important to mention several stakeholders. The stakeholders are separated into three categories. Primary stakeholders have direct involvement, secondary stakeholders are directly impacted, and tertiary stakeholders are indirectly impacted. The stakeholder map is shown in Figure 10.

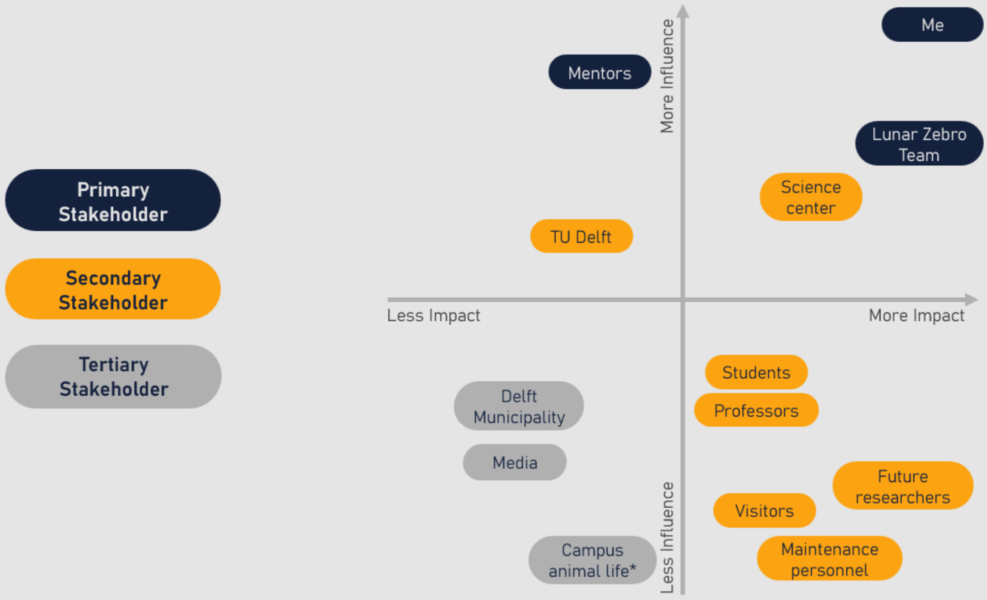

Figure 10 Stakeholder map showing primary, secondary, and tertiary stakeholders (*animals are not always considered stakeholders)

3.3 Scope

Considering the project context and stakeholders, the project is still too broad and large for the limited time frame. To further narrow down the project, let us clearly set the scope. A schematic overview is given in Figure 11. Starting from BID, the project focuses on the software and hardware but leaves out the technical aspects of Traici, considering the ES graduation. Although it is designed for Traici, testing may be done using other robots if Traici is not available. On the other side, the focus lies on sensing, expression, and HRI for the IPD graduation. The project will be designed to accommodate HSI, but due to time restraints, will stop at HRI.

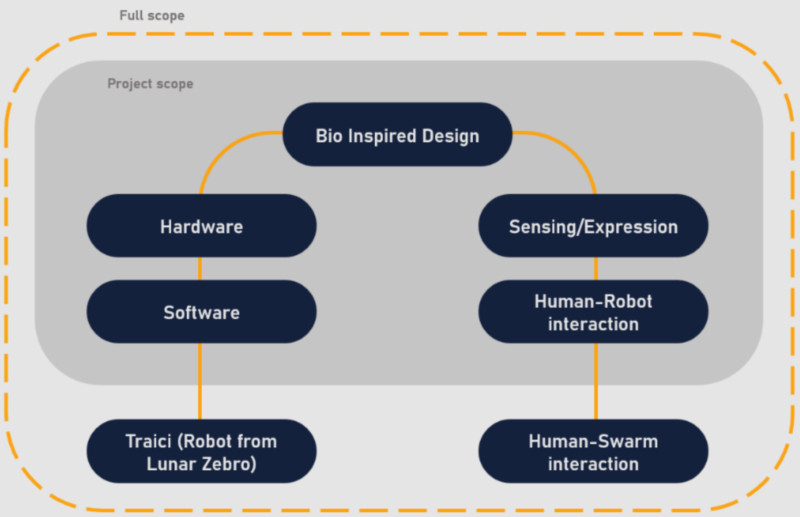

Figure 11 Schematic showing the project scope (grey) within the full scope (dotted orange line)

3.4 Embedded Systems and Integrated Product Design

To make a clear separation between the whole project and what is discussed in this report, Figure 12 is given. This report focuses on the interactions, aesthetics, and mechanical design.

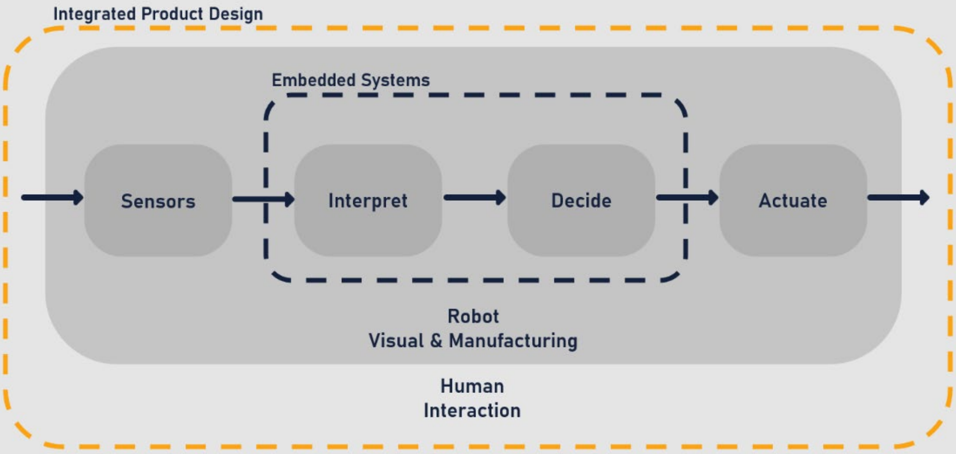

Figure 12 Overview of the whole project, with in orange the focus of this report and in dark blue the focus of the Embedded Systems report

3.6 Vision

This leads to the following vision that comes from identified knowledge gaps, the problem statement, and the combined interest of the graduate and supervisors:

"Designing a bio-inspired symbiote that aids swarming robots in sensing the environment and expressing themselves to humans in an intuitive way"

3.7 Research Questions

To achieve this vision, this report aims to answer a few research questions. These research questions guide the reader through the report and try to tackle the challenges that come with the orange words in the vision:

- What **bio-inspired** features can be used to create intuitive interactions?
- What technical requirements should the symbiote adhere to be implementable for **swarming** robots?
- How should a robot **intuitively** respond to a human in an interactive setting?
- What sensing capabilities does the symbiote require to **sense** human emotions?
- What should the symbiote do to **express** its emotions to a human?

More specifically, the objective for this project and case study is:

"Building a robotic artifact to add to the Cyber Zoo that can interact with visitors on itself or via attaching itself to Traici, Mirte, or any other (swarming) robot"

4 Exploration

After the problem definition, it is time to diverge again, as shown in the double diamond in Figure 3. Sometimes it is helpful to step out of academia and look into the world. In the following sections, we will go over some of these experiences. After this, we continue with sections discussing the inspiration, prototyping, and exploratory tests.

4.1 Culture & Conversations

Here, we will discuss some cultural inspirations and conversations. Looking at a cultural context and talking to experts helps gain valuable perspectives.

4.1.1 Museum

The Museum of Technology in Ghent, Belgium, has a small exhibition on swarming technologies, as shown in Figure 13. Here, they showcase several innovations surrounding SR, with one of the examples being the Kilobots by MIT. In our definition, Kilobots are not real robotic swarms as they lack autonomy. However, they can still serve as inspiration.

The museum presented the advantages of swarm robots over ordinary robots and discussed some of their use cases. Furthermore, it showed different swarming robots accompanied by their design choices. These designs helped as inspiration for several structural and sensing solutions for the module's final design.

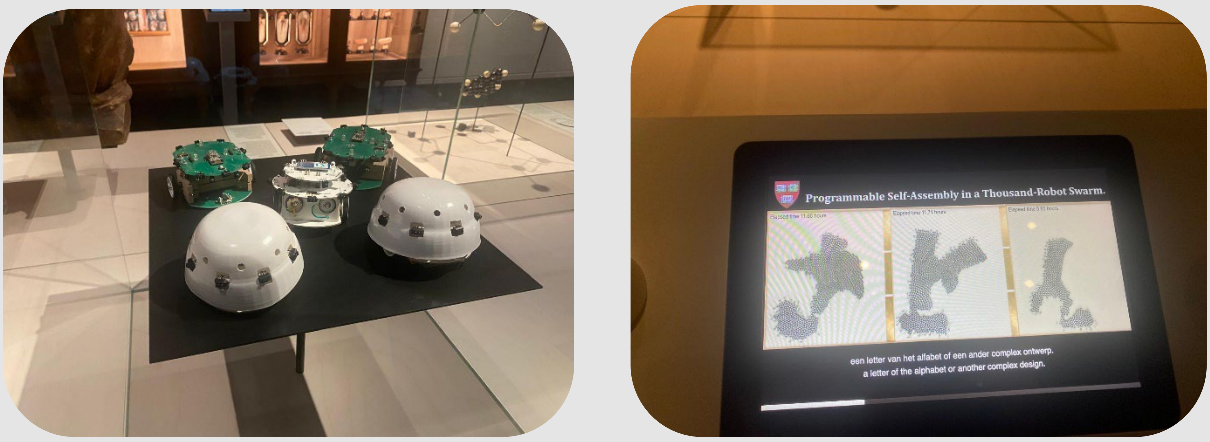

Figure 13 Swarming technologies are shown at an exposition at the Museum of Technology in Ghent.

4.1.2 Flow

The movie "Flow" presents a unique and immersive depiction of animal interactions, emphasizing naturalistic behaviors rather than anthropomorphized traits. The film's characters—a cat, a capybara, a lemur, a bird, and a dog, as shown in Figure 14 — Communicate and cooperate using movements, body language, and subtle vocalizations, mirroring real-world animal dynamics. Their interactions showcase complex social behaviors such as trust-building, conflict resolution, and mutual aid, which emerge organically as they navigate a post-apocalyptic flooded world. The absence of dialogue reinforces this authenticity, allowing viewers to focus on non-verbal cues and interspecies relationships.

Although the module might not be able to capture the full communicative range of these animated animals, the exaggerated movements helped detect them, which could be helpful for the project. These movements were written down and later discussed with a dog training expert.

Figure 14 The main characters in Flow – a movie about animals interacting and working together in a post-apocalyptic flooded world

4.1.3 Dog trainer

After watching the movie mentioned above, the findings were discussed with a dog trainer. The dog trainer specializes in dogs with problematic behavior but has much experience with other dogs. This was done for several reasons. First of all, it is useful to validate the findings, as some might not be entirely correct. Secondly, the findings functioned as a foundation for a constructive conversation. Lastly, together with the dog trainer, I could discuss which movements are more relevant, grouped, or animal-specific. Combining this with the overall design, other findings (e.g., from the test mentioned later), and ease of technical implementation, a selection was created. The findings will be discussed at the end of this chapter. The dog expert helped with the selection of ways of expression.

4.2 Direction

Before deciding on the form and function, it is important to look at different places for inspiration. When creating something that can help a robot with expression and sense to have more meaningful and intuitive interactions, it is good to look at where this is already happening in nature.

4.2.1 Inspiration

The two primary inspiration sources for this project were the dog and the arthropod. Both for very different reasons. The dog is easy to read and most intuitive, whilst the woodlouse, inspired by LZ's current form, could allow for novel interactions.

Dogs

- Easy to read emotions
- Most research done
- Intuitive to most people

Arthropods (wood louse)

- Inspired by LZ
- Allows new appendages
- Work in groups

Figure 15 Inspiration sources used for the project, with reasons for choosing these sources.

Dogs

Dogs have lived next to humans for a long time. They have had many generations to better cater to humans and become better at showing emotions to us. People do not use the things other people say as much to determine emotions. **People lay way more focus on facial expression and voice intonation, as shown in Figure 16 (Mehrabian, 1971). Dogs have evolved to have clearer features to show their emotions, and vocalizations have been used to show intonations**.

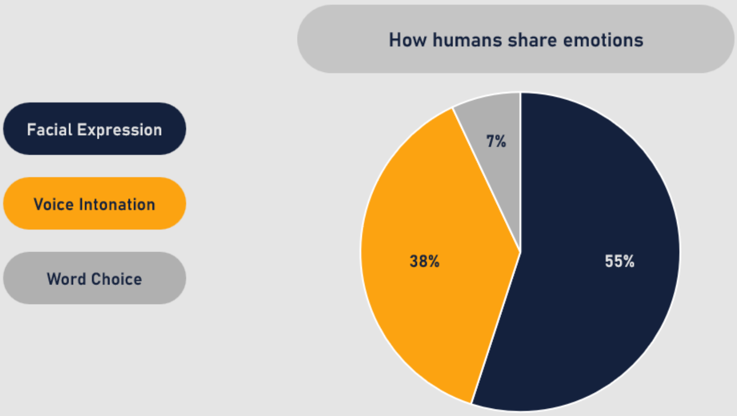

Figure 16 Graph showing how humans read emotions from other humans (Mehrabian, 1971)

The emotional markers of dogs have been well studied and documented. The five main points of interest are the eyes, mouth, ears, body/stance, and tail (LECA, 2019).

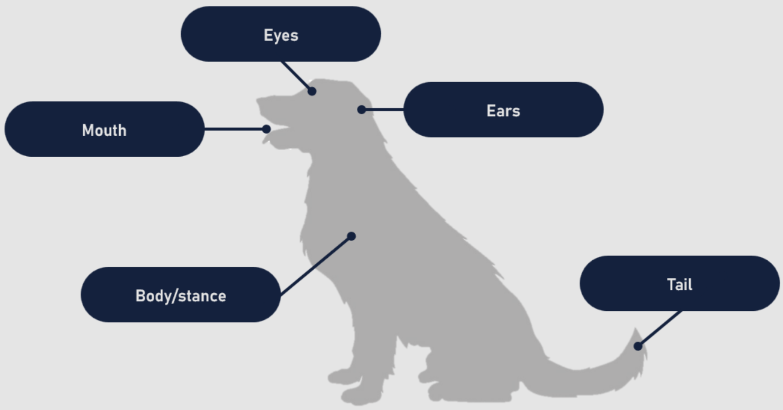

Figure 17 Most important emotional markers of dogs (LECA, 2019)

When looking at these markers, we can distinguish several emotional states. These are the most common distinguishable states found. Connecting all the markers or features to these emotional states, we get an overview as shown in Figure 18.

	Playful	Relaxed	Alert/ Interest	Stressed	Fearful	Defensive
Eyes	Dilated	Relaxed	Wide	Dilated	Looking away	Wrinkled frown
Ears	Up	Up	Forward/ Twitch	Back	Back/Flat	Forward/ Spread
Mouth	Open	Slightly open	Closed	Corners back	Licking	Curled/ Teeth
Tail	Up/ waving	Down	Flat	Down	Down	Up/ Stiff
Body/ stance	forward	Straight/ Loose	Slightly forward	Lowered	Lowered/ on ground	Forward/ Stiff

Figure 18 An overview of the five main markers (blue) and how to recognize the six central emotional (orange) states of a dog

Arthropods

Wood Louse and other arthropods, inspired by LZ, have a hard external body, less expressive ligaments, and antennae. This allows for new and novel exploration of interactions. The hard exteriors of arthropods also mimic the often hard exterior of robots.

Antennae are also an interesting feature for further developing sensing and material selection. Woodlice uses its antennae for navigation and observation.

4.2.2 Interactions in Animals

Interactions require a form of expression from one individual and a form of sensing from another individual. Both expression and sensing are performed using a feature on the body of that individual, e.g., eyes sense light and can express emotions.

Expression

An exploration through the HKJ method of different forms of expression is shown in Figure 19. It is done from the robot's perspective. Thus, it is the robot expressing something to the human. The second layer in the circle is the human sense, which is used to express information. The next layer shows the method it uses, and the outer layer shows examples inspired mainly by nature.

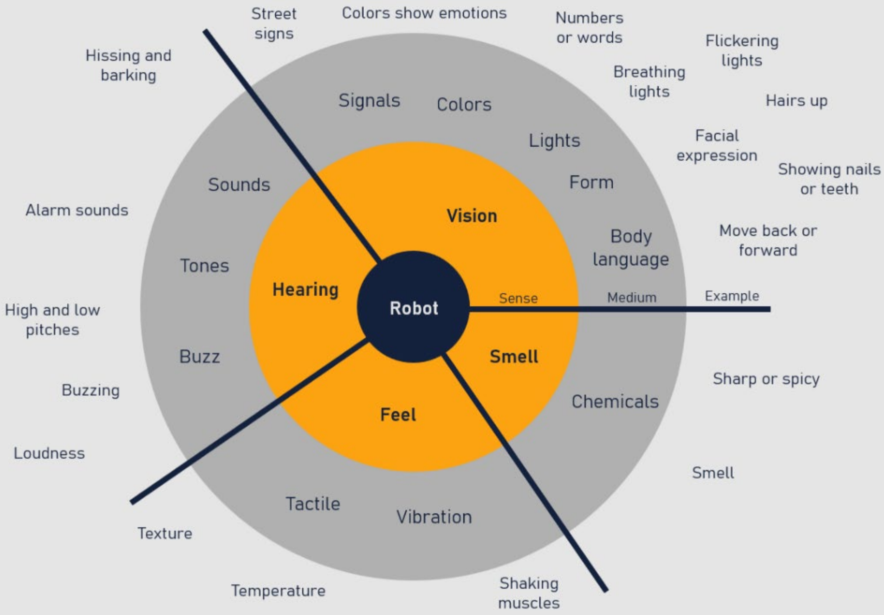

Figure 19 Schematic showing ways for a robot to express itself to a human through the HKJ method

Sensing

A similar exploration was done for sensing. This is shown in Figure 20.

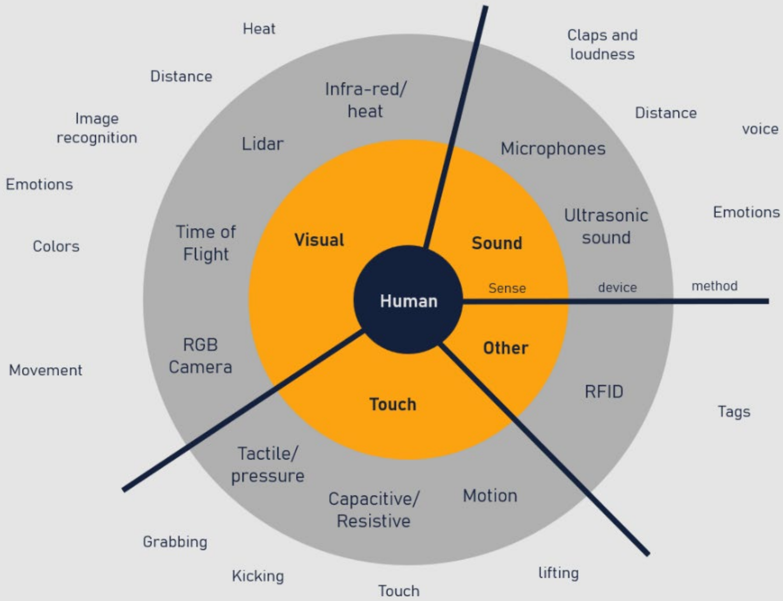

Figure 20 Schematic showing ways for a robot to sense a human through the HKJ method

Bio-inspired Feature

Looking at both inspiration sources and other animals, we can make a list of different forms of expression, sensing, and the features that allow for sensing and expressing. Figure 21 shows this list. The yellow boxes are the options selected for the first explorative prototyping session. The dark grey boxes are options that will be explored more after the exploration of the first options, and the light grey boxes are not used due to time constraints. The light grey boxes could still be explored in future works.

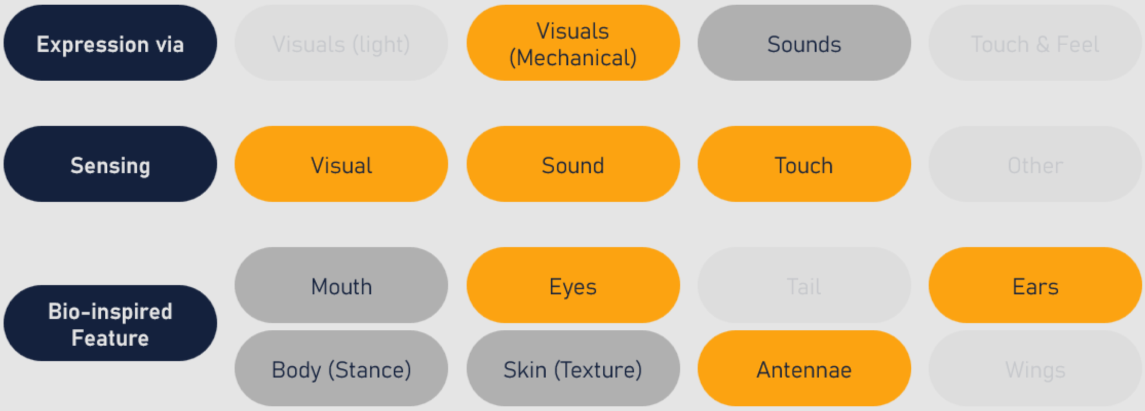

Figure 21 Schematic showing the chosen design options (orange) chosen for the first prototype during exploration for expression, sensing, and features, and showing secondary options in (grey)

4.2.3 Options

The first explorative concept designs are shown in Figure 22 through Figure 24. Although graphically different from its traditional form, the three options are chosen from a morphological chart as shown in Figure 21. In the end, I created two modules. One with eyes and antennae and one with eyes and ears. All features needed to be able to move in two degrees of freedom. The eyes and antennae rotate in two degrees, and the ears rotate in one degree and have an extra degree of motion for folding the ears.

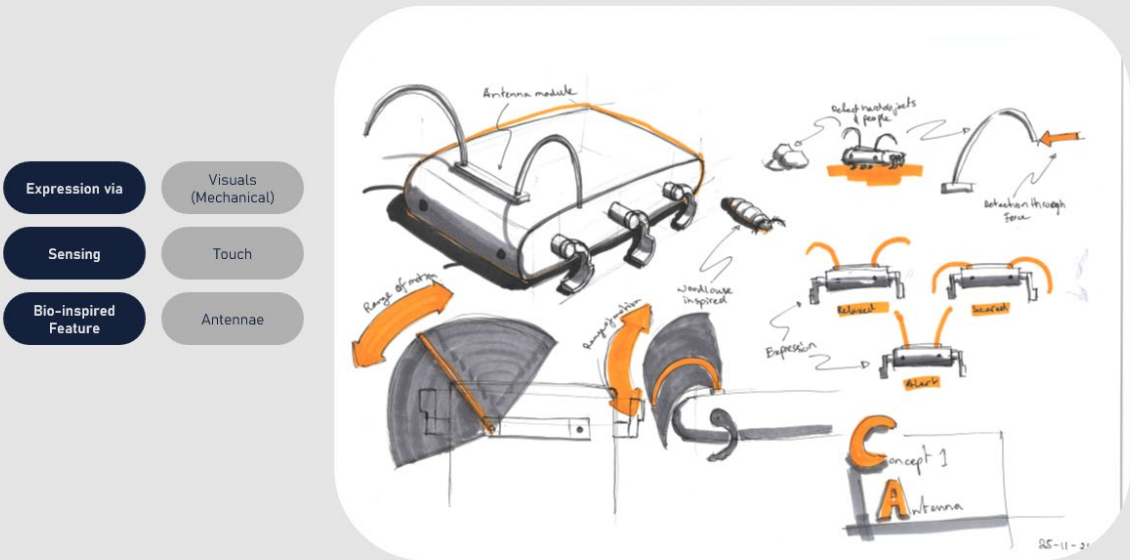

Figure 22 Concept drawing of the antennae concept with the chosen expression, sensing, and feature as chosen from the morphological chart

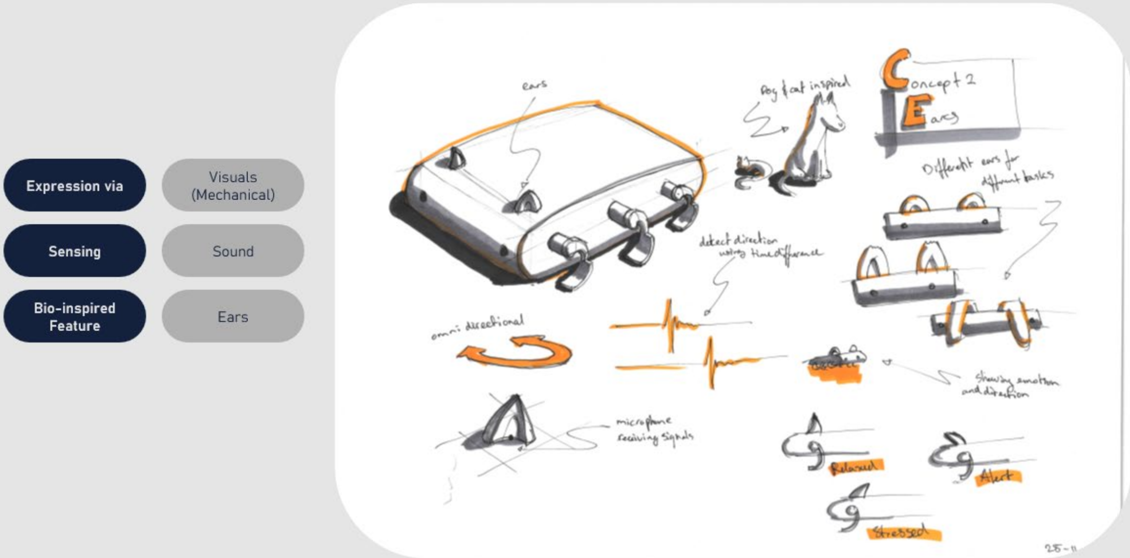

Figure 23 Concept drawing of the ears concept with the chosen expression, sensing, and feature as chosen from the morphological chart

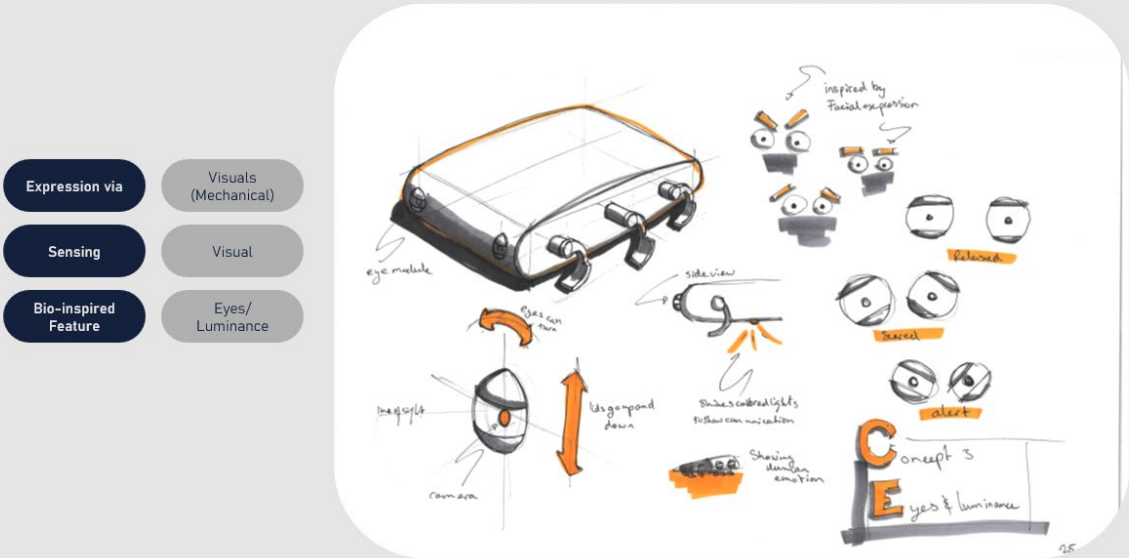

Figure 24 Concept drawing of the eyes concept with the chosen expression, sensing, and feature as chosen from the morphological chart

4.3 Prototyping

To facilitate the module, a rough one-to-one scale mockup of the LZ robot was made. This is done to give a better sense of scale and context later on during the test. The mockup is shown in Figure 25 (left). The modules are shown in Figure 25 (right). Both modules require eight servo motors to accommodate all degrees of freedom. The servos are controlled and powered by a PCA9685 breakout board. This board is connected via I2C to an Arduino WIFI REV 2.0 that is connected via Bluetooth to a controller, as shown in Figure 26. The controller layout can be found in Appendix B. The mechanical structure and the ayes were 3D printed out of standard PLA filament to accommodate fast prototyping. The ears and antennae were made out of 3D printable flexible 95A TPU to mimic real ears and antennae better and allow for bending.

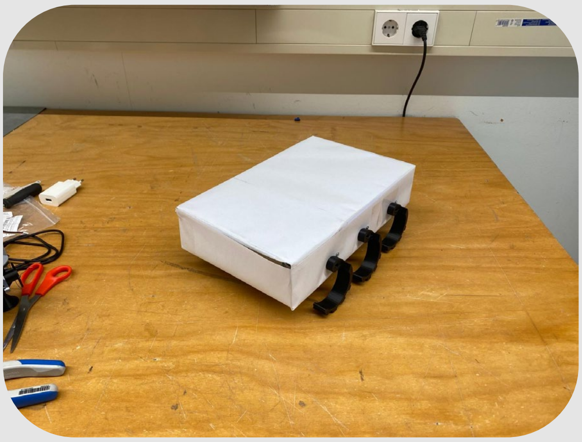

Figure 25 Mockup of the LZ robot (left), modules of ears and eyes on the left, and antennae and eyes on the right (right).

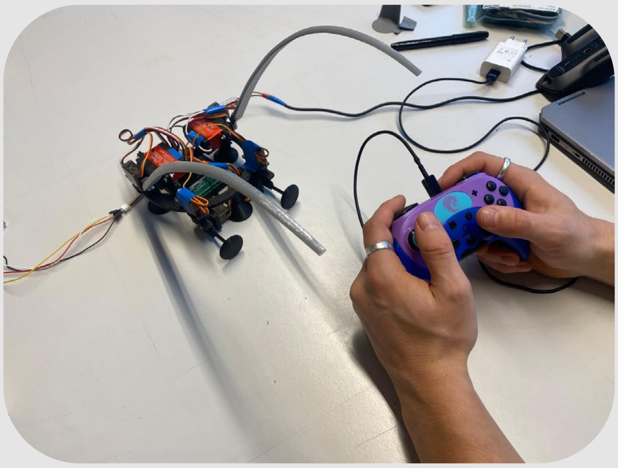

Figure 26 A Bluetooth-connected controller used to control features on the module

4.4 Test

The first explorative test was performed with the HRI group at the DUT. Here, the setup was as in Figure 27. This test was meant to get the first feedback on:

- The first three features
- How easy it is to read emotions from these features
- How consistently do people read emotions from these features
- Suggestions for improvements on the features
- Suggestions for other features
- Suggestions on improving future tests

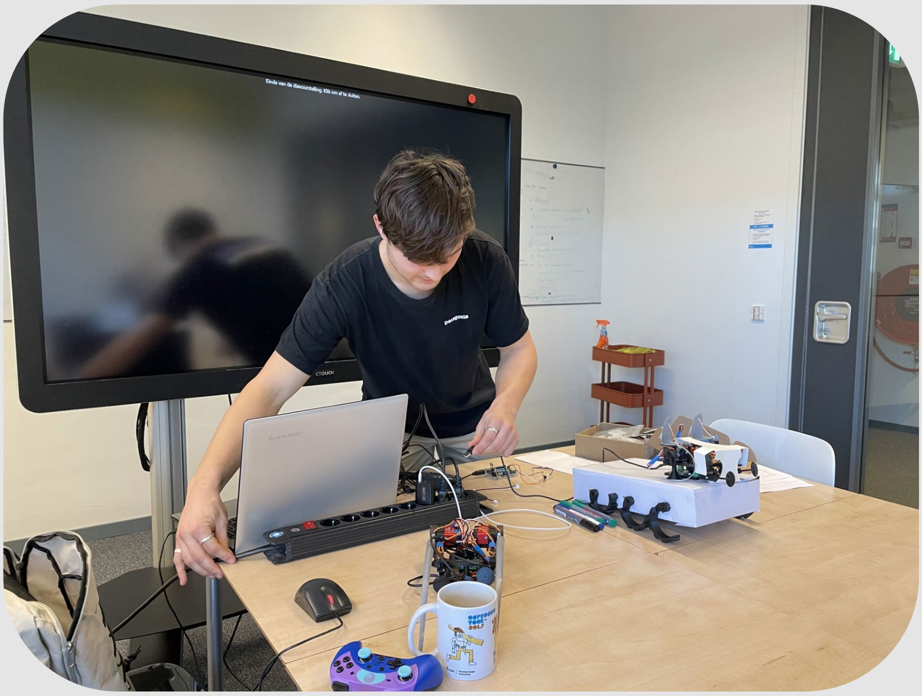

Figure 27 Test setup for the explorative test.

For the test, it was decided to create several emotional states. When in such a state, the robot would move between the given boundaries. The movement is calculated to have no jumps in speed to mimic natural movement. The graphs are shown in Figure 28. Each appendix can move separately from the others, but the eyes were synchronized to look more natural. When an appendix is standing still, it waits for a random time between 0 and t_wait seconds to move again. t_wait is a variable that can be changed depending on the state. When the time is reached, the appendix chooses a random location to move to that is further away than the minimum threshold (T_min) from its current location and within the outer bounds (x_min, x_max, y_min, y_max). It calculates a path using its maximum velocity (v_max) and the acceleration (a). All parameters can be altered per emotional state. **The emotions relaxed, playful, alert, and stressed were used as a sub-selection from the main dog emotions**.

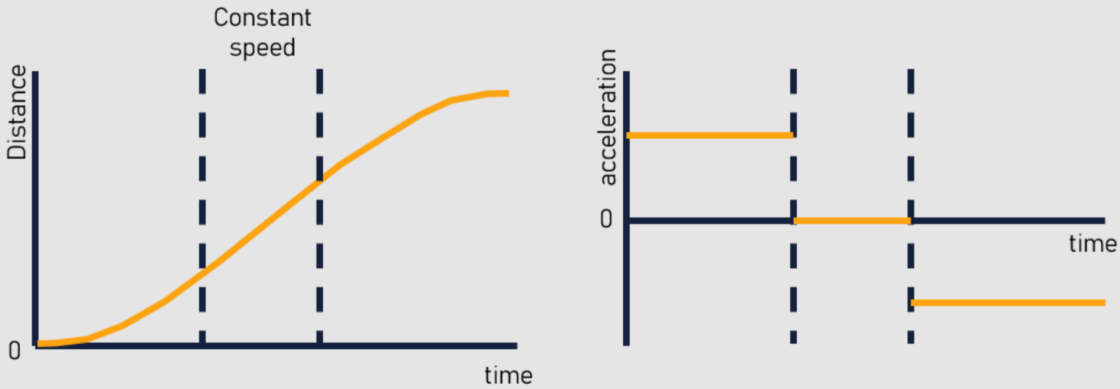

Figure 28: Graph showing distance against time (left) and acceleration against time (right) of the motion of the *appendages*

Manual control was also added to allow participants to set appendages in specific angles to explain how they felt or how they could be improved.

The test consisted of four emotional states per module. For each of the eight states, the participants were asked to rate how much of each emotion they felt was present in that state. The emotions they could choose from and the answer sheet are shown in Appendix D. Each participant was also asked to write down whether they had a dog or not.

4.5 Results

The results of the experiment showed that, first of all, **the number of participants was too low to obtain any relevant quantitative answers.** The results are shown in Appendix E. We can, however, notice that there seems to be a significant difference between the way dog owners answer the questions and the way non-dog owners answer the questions.

4.6 Improvements & Comments

The main takeaway from this experiment is qualitative. The discussions afterwards led to many suggestions (the less important in light grey):

- Adding:
  - Movement (legs, body language) for clarity
  - Add eyelids and pupils
  - Describing and introducing context
- Decide and have constant:
  - Orientation (can people move or not)
  - Proximity
  - On the ground or table
  - Have an audible noise or use a headset
  - Does the robot sense the person (eyes follow the person)
- Interesting:
  - A "do not pick me up" signal
  - Antennae can give a creepy vibe.
  - Read the paper: Florent Levillan – Behavioural object
  - The antennae are clearer than the ears

4.7 Findings

Here we will summarize the findings from the exploration and stipulate a way forward.

4.7.1 Robot Grammar

Although the test was not conclusive because of the low number of participants, it did provide interesting insights. The participants were all experts in the field of Human-Robot Interaction, meaning this qualitative research was extremely valuable. **The test showed that the communication of the robot (module) is in many ways analogous to a language, with its own "grammar". Here, the appendages are tools like vocabulary and hand gestures to our language**. After discussing the results with the participants and telling them what I intended, they could see the emotions more clearly and understood what to look for. This is, of course, similar to when people learn the grammatical rules of a new language. Here you learn general rules and apply them in different contexts. This is also similar to humans interacting with animals. People who do not have pets are more awkward around dogs and cats, whilst pet owners often do not struggle with pets from other owners. Creating a clear "grammar" for the module should thus be the priority. This will be done in the next test using a brief introduction for the participants, where a few contextual scenarios are shown beforehand.

4.7.2 Features

For the appendages, the antennae and eyes were chosen as the better option. This was because it communicated more clearly. One reason was the size of the antennae compared to the size of the robot. Here, small ears were less visible, especially when placed on the ground. The second reason for choosing the antennae over the ears is that they allow for more interesting follow-up research, which is a significant motivator for the project. However, if time allows, an ear submodule will be explored. **The final selection of features has changed from Figure 21 to that of Figure 29**.

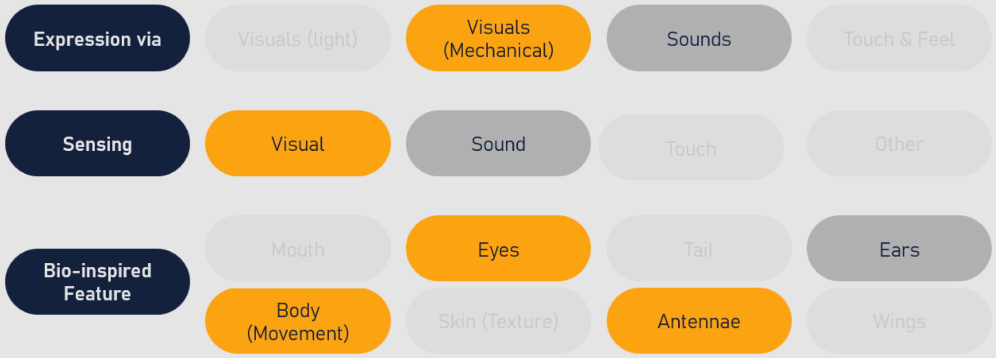

Figure 29 Schematic showing the chosen design options (orange) chosen for the ideation phase for expression, sensing, and features, and showing secondary options in (grey)

4.7.3 Movements

Lastly, the movements of the features. These were chosen through the movie, conversations with the dog expert, and the explorative test.

Eyes

In the explorative test, both eyes could move separately. This not only requires more hardware and more software calculations when synchronized, but also causes confusion. Next to that, separately moving eyes gave the participants an uneasy feeling, with one of them even saying they thought it was gross. Because of this**, it was decided that the eyes would move synchronously.** The movement of the eyes is shown in Figure 30.

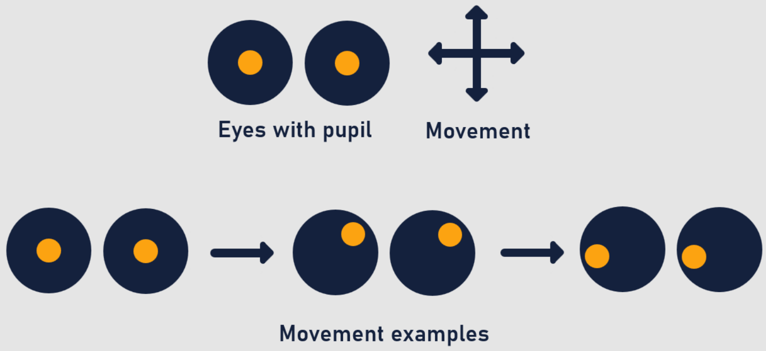

Figure 30 schematic showing the possible movement direction (top) and movement examples (bottom) of the eye with pupils

The movie and the dog expert made clear that eyes without eyelids would not suffice in properly conveying much emotion. Something is also lacking in the first prototype. For the eyelids, two options were discussed. Both options had the lids moving up and down, as is seen in humans. The difference was that one option would have the lids slant inwards or outwards, as can sometimes be seen in cartoons. However, this was deemed both technically challenging and mimicked eyebrows, which could be added with more ease and would be easier to read. The lid movements are shown in Figure 31.

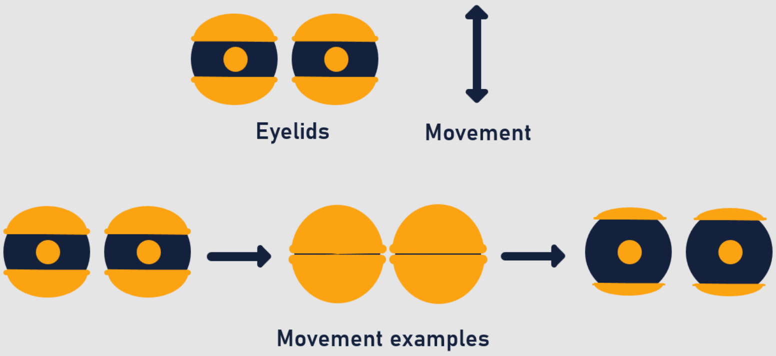

Figure 31 schematic showing the possible movement direction (top) and movement examples (bottom) of the eyelids

Antennae

The antennae are different from the eyes. Both antennae have two degrees of freedom but can also move separately from each other. This is similar to its biological equivalent, the woodlouse. This way, the antennae can be used in more than one way. Synchronous or waving motions could be used whilst exploring a room, whilst a mirroring motion could be used to mimic the behavior of dog and cat ears, and moving just one could be used to gesture to people. The movement of the antennae, as seen from above, will be over a full 180° range, as seen in Figure 32. This way, **the antennae can mirror dog and cat ears to show certain emotions, which will be helpful in building the emotional grammar**. Besides the rotational motion, the antennae can both move up and down, again, separate from one another, as shown in Figure 33.

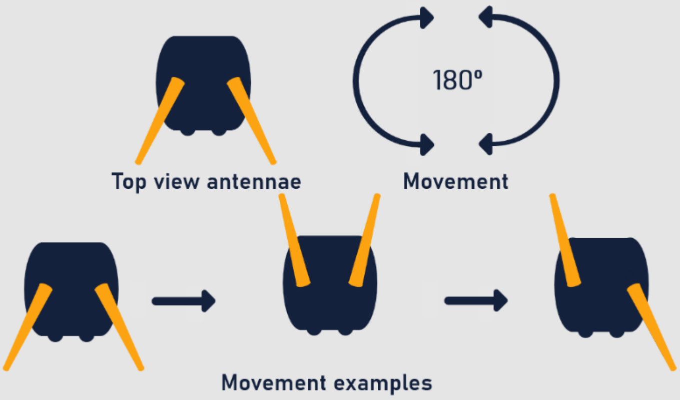

Figure 32 schematic showing the possible movement direction (top) and movement examples (bottom) of the antennae as shown from above

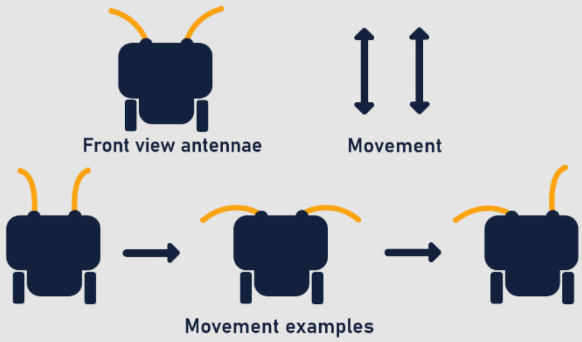

Figure 33 schematic showing the possible movement direction (top) and movement examples (bottom) of the antennae as shown from the front

Body movement

After the tests and conversation with the dog expert, it was clear that body movement is crucial for emotional conversations. Although body movement is not strictly part of the module that will be created, it is crucial to test it in tandem with some body movement. The unavailability of a Lunar Zebro robot during the project led to the use of a Mirte robot (TU Delft, 2025). A robot of similar size to the Lunar Zebro was used and created at the Robotics faculty of TUD. This robot lacks legs, which means body posture is not possible, but it has wheels that allow for movement from front to back and steering. **The paper by Florent Levillan (2017) on objects and their behavior also shows that movement of any kind can be attributed to a behavior by humans. Showing the importance of constant movement, even when it is only a slight movement.**

5 Ideation & Conceptualization

This chapter will discuss the ideation and conceptualization of the project. It will treat the design of all features mentioned in the previous chapter and will use the takeaways from the explorative study. Each feature has expressive and/or sensing capabilities. After all features are discussed, the integration and design are presented.

5.1 Eyes

The eyes of the robot are its primary mode of communication. In humans and animals, eyes are incredibly versatile when expressing emotion. This also follows from the results in the explorative study. Besides that, they also allow the robot to give attention to a specific individual by looking in their direction.

Next to its expressive capabilities, the eyes have sensing capabilities. Humans are highly reliant on them. They allow them to scan their surroundings, recognize people, and much more. The robot will mimic some of these attributes.

5.1.1 Expression

First, let us discuss the expression of the eyes.

Mechanical or Digital

One of the first important design decisions for the eyes is whether they should be mechanical or digital eyes. Digital eyes, or eyes on a screen, are far easier to implement. However, in different lighting conditions and from sharper angles, they can be barely visible. Furthermore, because the eyes are the primary expressive mechanism, they should allow for the most expressive capabilities possible. **When discussing different examples with participants, every single one of them preferred the mechanical (or animatronic) option**. For good reasons, both Disney and the Efteling use them throughout their theme parks, as shown in Figure 34. In short, these animatronic eyes look more realistic and are better at capturing and conveying emotions.

Figure 34 Pictures of the animatronics used in the Disney theme parks (left) and the Efteling theme park (right)

Eyelids

Another remark was that the eyes needed eyelids. In faces, eyelids can convey many things, and in the work of Ekman (1993), this is further shown. His work will be used a lot more in the interactions chapter. **Wide-open eyelids can convey fear or stress, whereas barely open eyelids convey a relaxed mood.** Similarly to the eyes, these will be made as mechanical parts. The last thing eyelids add is idle movement, like blinking.

Without eyelids, the eyes cannot provide enough emotional expression. Another place of inspiration for this is the world of animation. In animation, the eyes are primarily used to express emotions. Because of this, the eyes are often drawn larger relative to less important features. For this reason, the eyes and eyelids will be made extra-large to have a significant color contrast. In this way, the eyes are more clearly visible.

Movement

Eyes and eyelids generally move synchronously, except for winking or looking cross-eyed. Mechanically connecting the eyes makes sure that no software mistakes can accidentally change this synchronous behavior.

Next to this, the movement speed is important. Faster movements convey a more stressed state, whereas slower movements seem to be more relaxed. Furthermore, using the smooth motions from the explorative tests provides a natural behavior.

Visual

The look and feel of the eyes is critical. Relatively larger eyes are perceived as "cuter"; these are found in babies and puppies. Larger eyes and the color difference between the lids and the eyes also help the eyes pop. This results in a more visible and more apparent expression.

The eyes were given pupils and irises, in a bright color. Different colors were tested and shown in Figure 35. The results were obtained through user interviews of five people. The black iris was perceived as "dumb" or "cartoonish"; the red iris was perceived as "dangerous" or "mean"; and the green was perceived as "friendly**". Because the robot will be performing interactions at the science center, as well as with children, friendly green eyes were chosen.** The black pupil provides a significant contrast with the eyes.

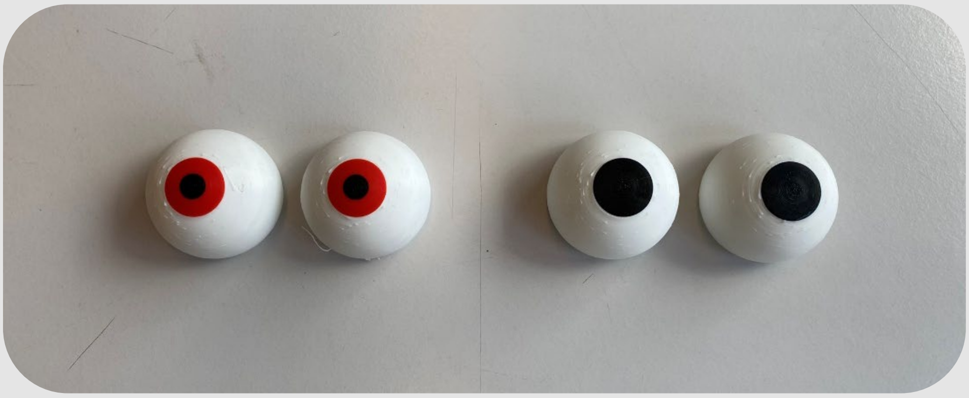

Figure 35 Different iris colors that were tested

Eye Mechanism

The eye mechanism was tested as in Figure 36. It shows that the eyes are protruding and thus visible from the side. The eyes are connected using a rigid bar with hinges in both the x and y axes. In this way, the eyes are always looking in the same direction.

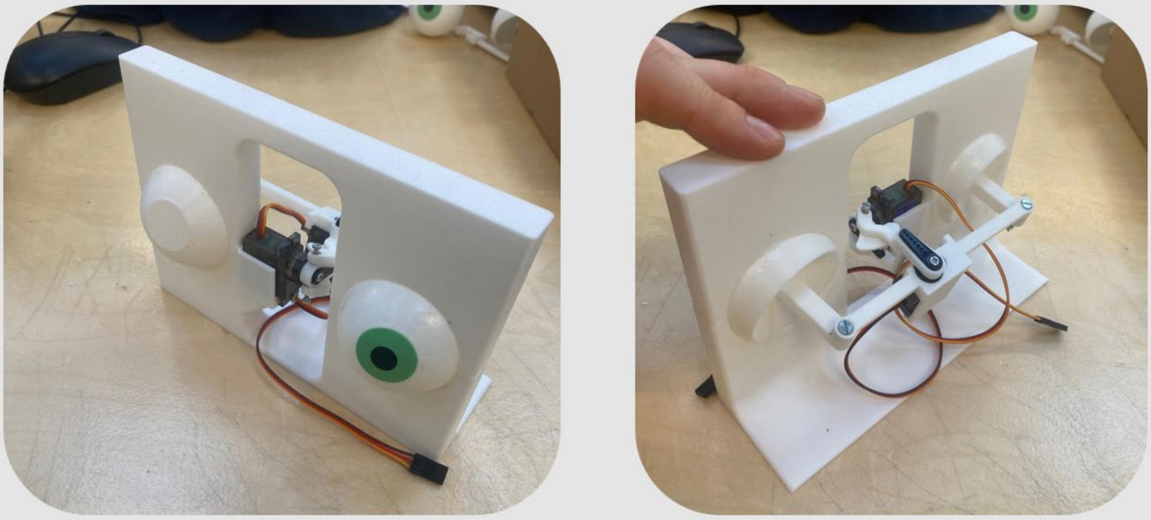

Figure 36 Picture of the prototype of the eye mechanism

Eyelid Mechanism

The eyelid mechanism was made in black to contrast with the white of the eyes. Figure 37 Shows the eyelid mechanism prototype. The eyelids are placed over the eyes and require a method for opening and closing. The first method that was tested used springs in the corners of the eyelids to push them closed and used a string to pull them open, inspired by old voltage meters (where the current is proportional to the force pulling on the spring). However, the 3D printed material could not stand the forces and tore as seen in the left image. The second method is more akin to the methods used by Disney. The eyelids are connected via a rigid structure to a servo and controlled from a distance. This is shown in the right figure.

Figure 37 Pictures of the eyelid mechanism prototype, with on the left and middle the eyelids, and on the right the chosen opening and closing method

Now to combine both in Figure 38. **Here you can see that, without any movement, the eyes already show a lot more emotion than without the lids.** Furthermore, the contrast nicely shows the expressive capabilities of the eyes.

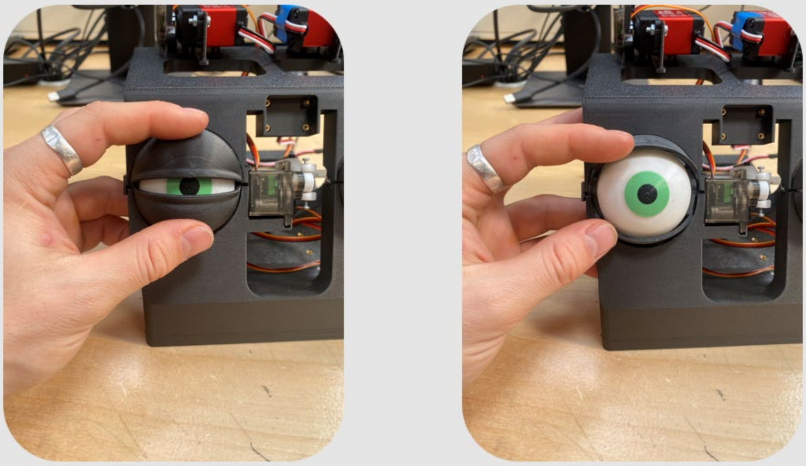

Figure 38 Picture of the prototype showing the eyes and eyelids together with the contrast between the black and white filament

5.1.2 Sensing

For visual sensing, many options are available. Choosing the right option is critical as it determines the sensing capabilities, measurement speed, and, in the end, the interaction itself. As suggested after the explorative test, looking at a person is important to show active engagement of the robot. Looking at someone requires two things: detecting people and choosing the right person to look at. This can be done in several ways. The two most promising are discussed here. However, in the sensing section (Rozendaal, 2025), this is discussed in more depth.

Distance Sensor

Distance sensors can help with the question: Who do we look at? A good solution would be the closest person. A distance sensor could help with finding the closest person, but it cannot detect people on its own. Although it is cheaper both in cost and data processing than a camera, it lacks in human detection. However, it could complement it.

Cameras

Cameras require more processing power, but with proper processing, they can find humans. A colored camera is best suited to find humans reliably. For an IR camera, it is difficult to distinguish humans from other hot objects. Furthermore, human detection has already been implemented successfully many times before and provides the most interaction options for the rest of the project. These interactions are discussed in the Interaction Design chapter.

Choice

The final choice was the Pi Camera 3 wide, shown in Figure 39. This Camera has a viewing angle of more than 60 degrees in both the x and y directions. This is important because the robot should be able to see the people in front of it. The Raspberry Pi products are also widely available and stay in stock for a long time, meaning they will be available for years to come. This camera has a high resolution of 4608 x 2592, allowing for all the desired interactions explained later (face, body, and emotion recognition).

Figure 39 The Pi Camera 3 Wide is used in the robot

5.2 Antennae

The antennae have no sensing capabilities but can only be used for expression, however, this could be interesting for future work. However, the way the microphone in the symbiote is used functions similarly to the antennae of cockroaches and similar animals.

5.2.1 Sensing

The antennae sense using the microphone. **The microphones work more like an antenna than like an ear. This is because the microphone is used to detect the loudness of the sounds and not for any form of speech processing. This mimics antennae that can feel vibrations through the air.** This way, the robot can respond to loud noises in the room. The microphone that was chosen is the Adafruit MAX4466, as it allows for the implementation of voice recognition and processing in future work. More on the sensing is discussed in (Rozendaal, 2025).

Figure 40 The Adafruit MAX4466 microphone used for the robot

5.2.2 Expression

For the expression, the path of the explorative test is continued, with inspiration in arthropods for the looks and dogs for the stances.

Movement

The antennae move asynchronously, just like with cockroaches. This means both antennae can move separately from one another. However, the movements and stances of the dog's ears were used. **This is done because the emotional grammar of dogs is well known, and that of insects and arthropods is not.**

Again, a smooth movement was used where speed and acceleration helps to determine the expressed emotion.

Visual

Visually, the antennae were chosen over the ears because they were physically larger. Because the robot is small compared to a person, and it is positioned on the ground, larger appendages are desired. This is also the reason for the length of the antennae. Longer lengths can be tried in the future, but the length was limited by the production method (the diagonal size of the 3D printer). The design of the antennae was not changed after the explorative study.

Material Selection

The materials that were chosen were selected mainly on their "Hardness". This refers to the shore value of the material. The tested materials, TPU and silicone, have a shore A value of 90 and 30, respectively (see Figure 41). Many more materials with different shore values should be tested, but for this project, the TPU worked and allowed for testing different shapes.

Figure 41 Shore A value scale with the tested materials shown.

Possibilities

New materials could allow for interesting forms of control, especially when entering the realm of soft robotics. Softer materials could allow the robot to pick things up, and stiffer materials could allow for pressure measurements. These pressure measurements could be used to mimic the touch sensitivity in the antennae.

Design

The design of the antennae is shown in Figure 42. The grey color lets it stand out on the black background, and the bent shape shows that it is made out of a flexible material. To fully utilize the flexibility of the material, the antennae are tapered towards the top. This way, the bend is larger towards the tip.

Figure 42 Picture of the prototype antenna used in the robot

The old design was repurposed but improved in several ways. The antenna holder was made symmetrical to be used on both sides, round so that it could properly turn 180 degrees, with a cable groove, and closed off in its housing with a cap. This cap was made smooth to fit the aesthetic of the rest of the robot.

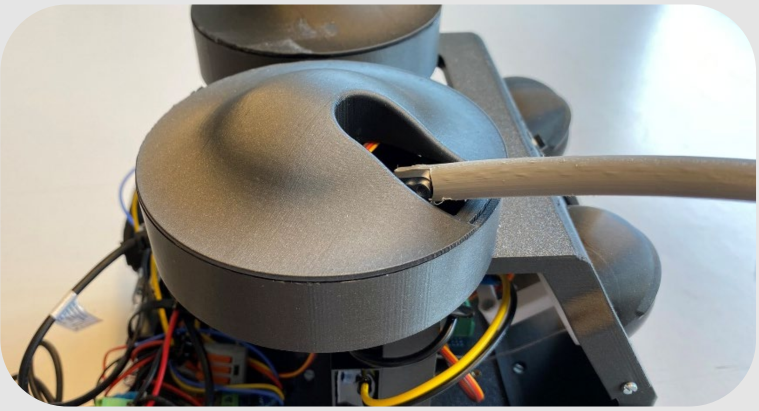

Figure 43 Picture of the antenna holder with the improvements and the antenna holder with the cap

5.3 Body Movement

Lastly, the body is only used for its expressive capabilities. It is important to note that the symbiote would eventually function as an addition to another robot. **In this case, the host would take care of the locomotion, and the symbiote would only give instructions on how to move to express itself. However, for this project, the body movement is performed using the skeleton of a Mirte.**

5.3.1 Expression

The frame that was used for the expression is shown in Figure 44. The frame, wheels, and motors were used as the host for this symbiote. This was necessary to show the full capabilities, as movement is an integral part of the emotional expression.

Figure 44 Picture of the robot frame used for the locomotion of this project

Legs and Wheels

The Mirte robot was chosen because the Lunar Zebro robot was unavailable during this project. Unfortunately, this limits the movement capabilities. The stance and pose of an animal tell a lot about its emotional state. Nonetheless, we can use forward and backwards movements to mimic the stance. For example, instead of leaning forward, we can move forward. Furthermore, the speed of the movements helps in addressing the emotion.

Attention

Not only can the eyes give attention to a person. Moving the body towards someone can help in providing attentive feedback. This was also one of the discussion points in the explorative tests and the topic in the work of Levillain (2017).

Possibilities

In future works, this part of the robot would allow for many functional behaviors. For example, looking for people, following someone, or spreading over an area. **This makes the symbiote incredibly versatile. Because different robots using different locomotive systems can use the same symbiotic expression robot. This means people can interpret the emotions of different robots using the same emotional grammar.**

5.4 Integration

The first thing we will look at when integrating all these subsystems is the visual aspect. Figure 45 shows the ideation sketch of the visual appearance of the robot. The concept shows a “head” that could be placed on any robot. **The simplistic shapes steer the attention of the person towards the interactive elements**. The color was later changed to black, but the color difference between the body and the appendages remained.

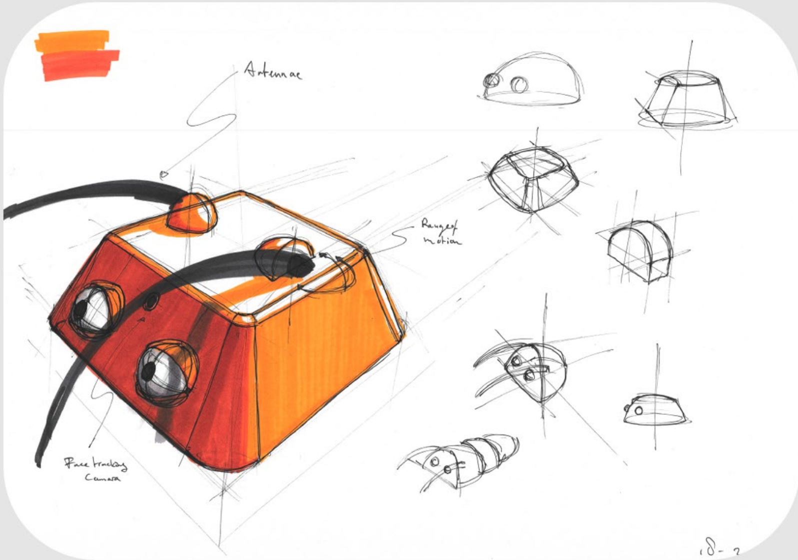

Figure 45 Ideation sketch of the visual appearance of the symbiote

The 30-degree mounting slope for the camera and eyes was chosen to make full utilization of the camera's wide-angle lens. In the context where the robot will function, it will be on the same level as the people it will interact with. Because the robot is much smaller than humans, looking up is required to have meaningful interactions. A bonus is that **smaller animals that look up to humans are perceived as less of a threat and seem more friendly.**

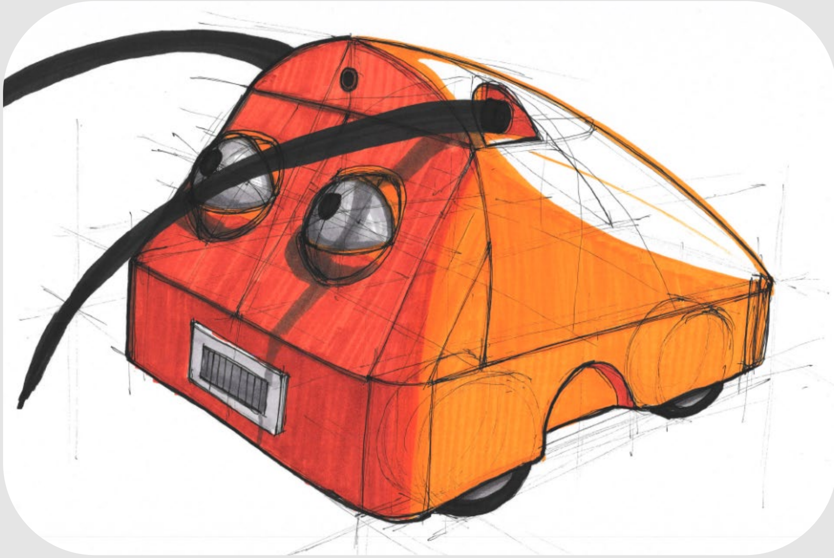

Figure 46 Ideation sketch of the visual appearance of the symbiote on top of a host

When attaching the symbiote to a host, it could look something like Figure 46. Here, the "Head" is placed on a frame with wheels – the host. The final design is made with 3D printed materials, meaning the color could easily differ for each robot. **Additional visual aspects, like freckles to hide the camera or using hairy print textures, could be interesting to pursue**.

The final integration of the symbiote on top of the host can be seen in Figure 47. It can be seen that the antennae are on top of the head in the antenna holders. This way, they can perform their full range of motion. Furthermore, the eyes, eyelids, and camera can be seen on the front with a 30-degree slope. With the entire frame on top of the host, as it will be in the Cyber Zoo.

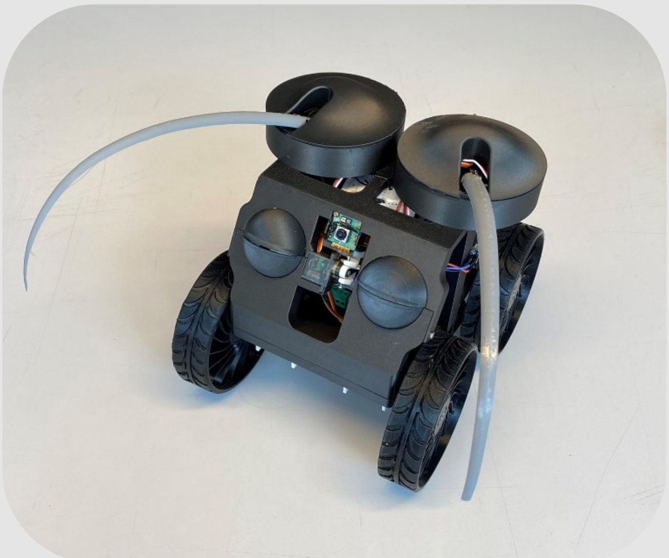

Figure 47 Picture of the final prototype integration of the symbiote on top of the host without the outer housing

5.5 The Design

The last step is designing the robot's housing or body. The bed size of the available printer severely limited this step. This design, limited by size, was created and printed. The render of the design is shown in Figure 48. This shows all expressive appendages in a different color from the body.

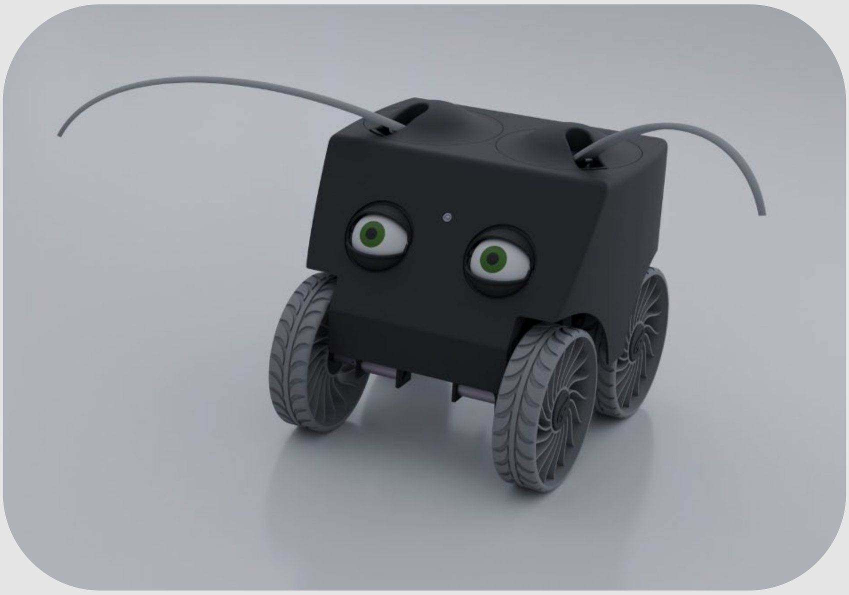

Figure 48 Render of the final design of the robot

Only two things remain: naming the symbiote and building it. The final built prototype is shown in Figure 49. It is shown in the context of a university setting. **The name should be friendly, bio-inspired, and easy to pronounce – in short, it should be a dog's name**. The chosen name is:

FLIP

Friendly Logic-based Interactive Presence

Figure 49 Picture of the final prototype build, in Mekelpark at the DUT

To summarize the decisions on features, let us look at Figure 50. In orange, it shows the expression, sensing, and features that are fully implemented. This is because the movement is not part of the symbiote itself, but the symbiote can instruct the host on what expressive movements can be performed. Secondly, it senses sounds, but only the loudness of the sound. This is closer to antennae that can measure vibrations in the air than actual sound processing. Lastly, expressive sound is something we have not discussed yet. **The movement in the servos makes quite a lot of noise. This noise is used as an emotional expression**. In short, faster movements give louder sounds and convey stress or fear, whereas slower movements give quieter sounds and convey a relaxed mood.

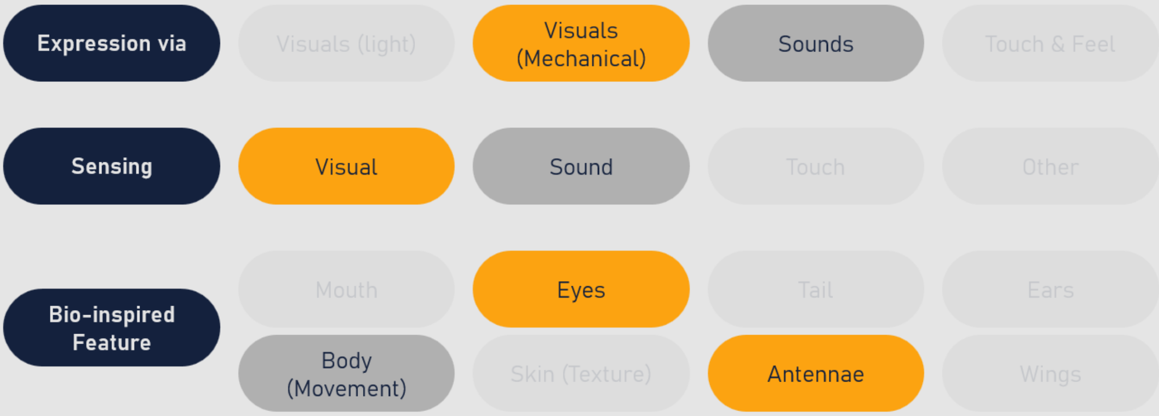

Figure 50 Schematic showing the final feature selection for the robot with the primary features in orange and the secondary features in grey

6 Interaction Design

Now, let us dive into the interaction design. Interactions are incredibly complex. To help the discussion in this section, it is divided into four parts that follow each other as shown in Figure 51. On the bottom is the human who shows behavior. What parts of this behavior are perceived as inputs depends on the sensors and how they are interpreted. The sensor interpretation is discussed more in-depth in the sensing chapter (Rozendaal, 2025). Then, a decision is made in the symbiote on how to respond. Lastly, this is shown on the output using the appendages. This is then, in turn, perceived by the human who can respond. **This continuous cycle is repeated, which is called interaction.**

The symbiote and human could, in theory, be replaced by any pair of responsive agents. Likewise, inputs and outputs may vary depending on the chosen frame of reference. What sets this symbiote apart from, for example, the animatronics at the Efteling is the presence of input. While people may react to animatronics, those animatronics do not adjust their behavior based on the human's response. In contrast, the symbiote does.

This chapter will go over all four stages of the interactions. It will use terminology that is linked to dog behavior, as this is the main inspiration for the interaction design. However, all relevant terms will be explained when discussed.

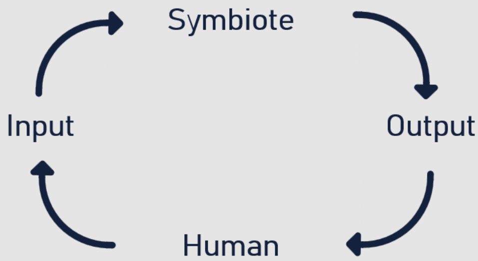

Figure 51 Simplified schematic showing the four stages of interactions between the human and the symbiote

6.1 Human Behavior

Just like interactions, human behavior is incredibly complex. **Simplifying and creating an accurate understanding is the start of creating an intelligent system (Brooks, 1999)**. For this reason, we will start simplifying human behavior. This section will shed light on several ways humans can express themselves towards other agents.

6.1.1 Emotions

The first expressive aspect of a human that we will discuss is emotion. Before doing this, we need to make clear what an emotion is. Let us return to the Merriam-Webster dictionary, which says: “a conscious mental reaction (such as anger or fear) subjectively experienced as a strong feeling usually directed toward a specific object and typically accompanied by physiological and behavioral changes in the body”. Immediately, some things jump out. **Firstly, directed to a specific object, in our case, the symbiote, and secondly, accompanied by physiological changes in the body. This is interesting because if we can detect these changes, then we can read these emotions.**

Facial Features

The work of finding the features in the face has already been done by Ekman (1993). He found that the seven most common emotions can be distinguished in the face by looking at several markers. This system is called the Facial Action Coding System (FACS). **These markers for the seven basic emotions, neutral, happy, fear, sadness, surprise, anger, and disgust**, are shown in Figure 52. Using this system, we can detect emotions and use them in our interactions. The implementation of this requires face detection and emotion detection, two well-researched, technically advanced topics. The implementation can be found in the interpretation section of (Rozendaal, 2025).

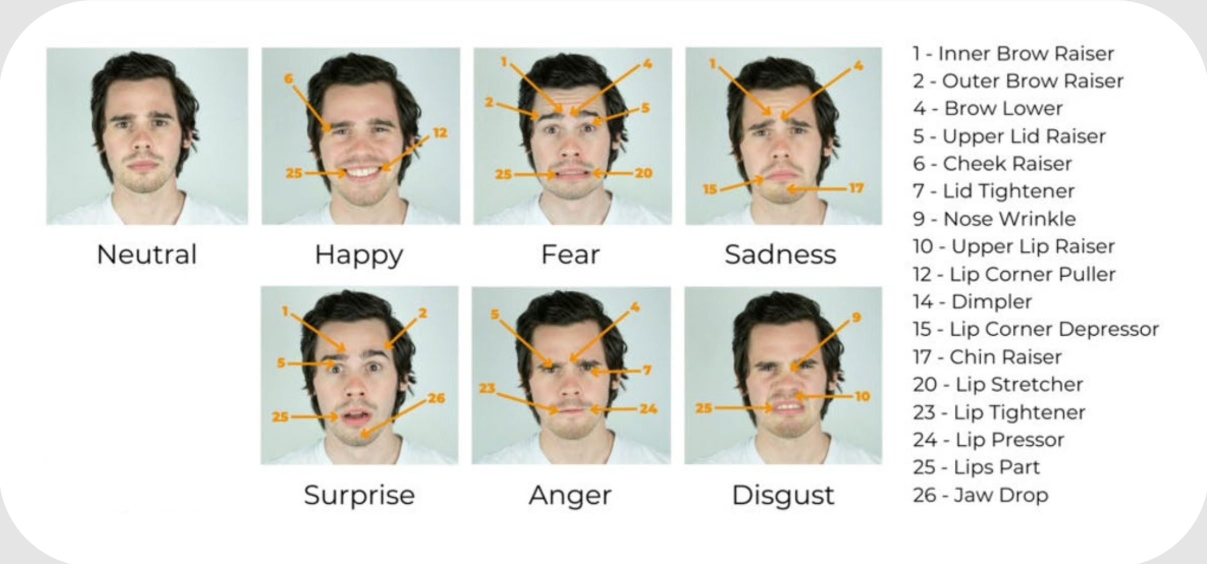

Figure 52 Showing the Facial Action Coding System markers used in Ekman's model (EIA Group, 2024)

Body Language

The second thing we can look at is body language. Body language consists of larger movements that are easier to spot. The body conveys information about the emotion and the dominance. Dominance is considered as it plays an important role in many human-animal interactions. Think about how standing tall can scare animals, while sitting low can help in approaching them.

Body language can be simplified to a few measurable metrics that have to do with the location of the person compared to the other agent: body size, height, and closeness. All three metrics are linked, especially when looking from the reference frame of the symbiote. A larger body size shows dominance, but could also mean someone is closer. Being taller or larger could scare smaller animals and make your overall size be perceived as larger. Lastly, being closer is more intimidating.

Other factors can also influence body language. Think about someone standing in front of you who is looking at someone else. You give this person no or almost no attention. Similarly, **if they turn towards you, they give their attention to you**. This can also be used to determine which person is more important in the interaction.

Lastly, movement, or the change in location. The speed, acceleration, and direction of movement provide much information about the way a person feels towards you. Movement towards you shows interest or aggression, depending on speed. In contrast, movement away from you could show fear or a lack of interest.

Sound

Much emotional information is in speech. As discussed, the exploration information lies in the tone and text. Although most information is still found in visual cues in the face, the second most important feature is the tone. **In tone, the easiest to measure and one of the most telling metrics is the loudness of the voice. A loud voice conveys anger or, in some circumstances, fear.**

6.2 Inputs

Because most human behavior is conveyed in visual and auditory signals, a camera and a microphone were chosen. However, what the microphone and camera actually detect and interpret deserves its own chapter. All the technical implementations can be found in the interpretation section in (Rozendaal, 2025). The four detection methods, with the inputs they receive, are shown in Figure 53.

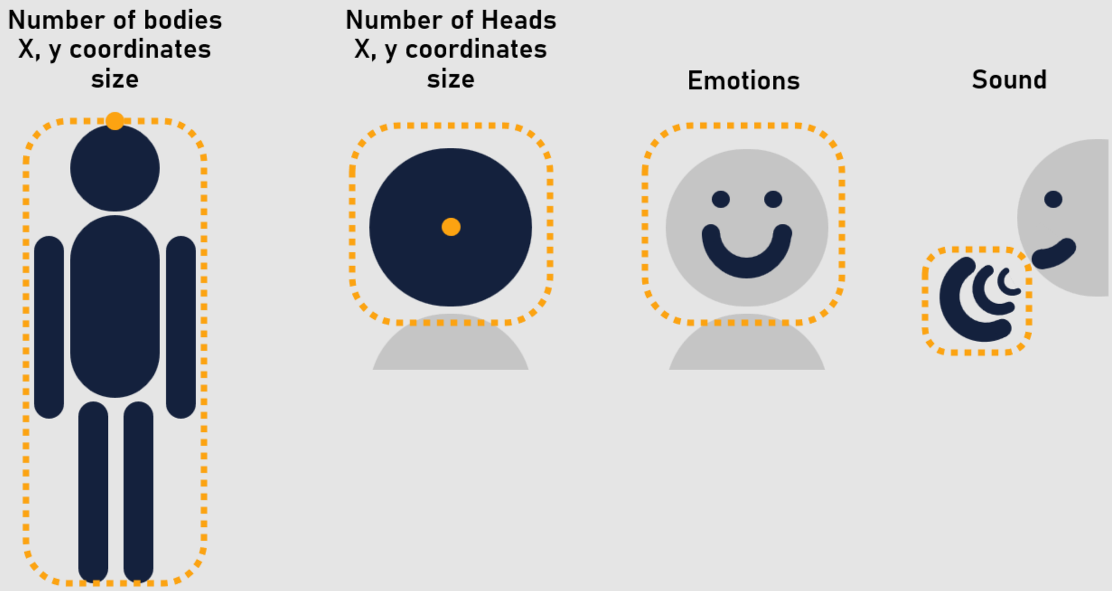

Figure 53 The four detection methods used by the symbiote

6.2.1 Camera

Using the camera, we can detect most of the interesting human behavior. The detection methods were chosen for the mentioned human behavior. It is important to note that this is in no way a complete description of human behavior. **This also implies that the inputs do not capture the full range of human behavior. However, the simplified model aims to create a starting point from which to work.**

Face Detection

Face detection was implemented using Haar cascade models. These are the same models that are implemented in digital cameras and other embedded systems that have limited processing power. The upside when comparing it to neural networks is the computation speed. The downsides are worse performance, especially on faces that do not face the camera. Furthermore, neural networks perform better on smaller faces compared to this model. Although I just called them downsides, let us interpret them in a way that the downsides aid us.

First, the worse performance on faces that look away from the camera. The fact that this model can distinguish between orientations of the face can be helpful. The distinction might be binary, i.e., it sees a face or it does not, but it does provide information. **A face that looks at the camera is giving its attention to the symbiote.** This would be the person the symbiote wants to give attention back to and respond to. This downside is that it does not function as a selection tool or filter for frontal faces.

Second, worse performance on distant faces. Not detecting faces far away helps us determine closeness. **Because the range of the face detection and the body detection is different, we can use the fact that no faces are detected as a confirmation that no person is close and paying attention.**

Emotion Detection

The face detection is used for emotion detection. Emotion detection relies on a pre-trained neural network. This is too slow to operate on the whole camera image. This means we need to cut the face out of the image and do the emotion recognition on the face alone. This is shown in Figure 54. **This way, the symbiote can recognize all seven basic emotions as mentioned above.** However, as will be discussed later, the final version of the symbiote does not use emotion detection because it hampers the responsiveness too much.

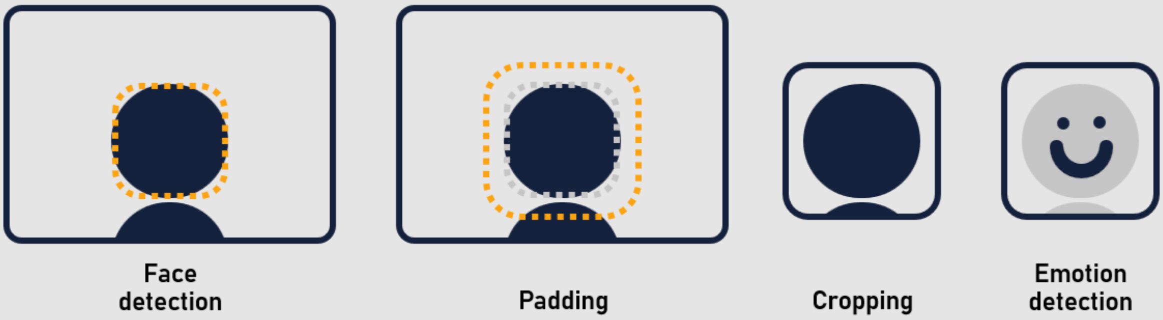

Figure 54 Processing of the face detection on a cropped image for emotion detection

Body Detection

Body detection helps us obtain more information from the same image. The range increase compared to the face detection is not the only benefit. As discussed earlier, the body conveys much additional information.

Giving faces the priority when selecting who to give attention to is a logical first step. However, determining who to give attention to when no faces are present is a different case. A good option is to look at the closest person. To achieve this, we can use a proxy for closeness. The proxy we can use is the body size. This is something that can be extracted from an image. This also works great when comparing the distance from multiple people. **The closest person is expected to be the largest**. This is not always true, for example, when a smaller person is standing next to a larger person. However, behaviorally, this makes sense. **Most animals would look at the larger of the two people standing in front of them.**

Using the body size, we can perform some temporal comparisons and detect movement from and towards the symbiote. This is shown in Figure 55. It shows how the difference in body size can be used to estimate how fast someone is coming towards or going away from the symbiote. This is a quadratic relationship that is used to make the symbiote more sensitive to movements close to it.

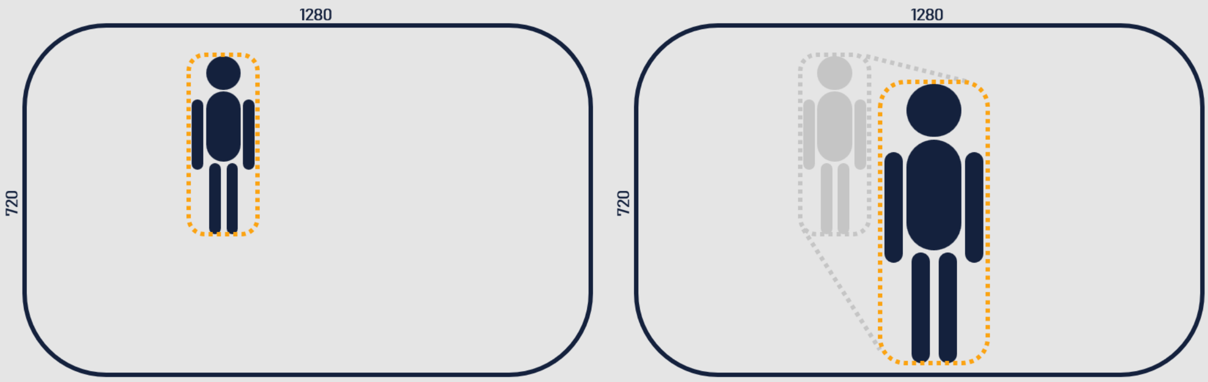

Figure 55 Showing how the change in body size over time can be used to estimate movement towards or away from the symbiote

Lastly, the height of the body shows how dominant it is in the image. Figure 56 shows how a less dominant position results in a lower height. This is also the reason we are using the area for the distance measurements. **Someone close and low should get the attention over someone far, but standing straight**. Attention will be discussed more in the next section.

Figure 56 Showing how the height of a body in the image shows the dominance of the person

6.2.2 Microphone

The microphone is used for noise inputs. We explicitly state noise and not voice because the symbiote, in its current form, cannot distinguish between sounds. The microphone does allow this, but it has not been implemented yet.

Loudness Detection

When we are just doing loudness detection, the signal integrity matters a lot less than when we want to process the sound. Thus, we can use the microphone with a high gain. This makes it easier to detect louder noises. The clipping of the sound is something we do not care about. Figure 57 shows how the detection band is larger for a higher gain, but how signal loss can take place.

Hearing

Actual voice processing or sound recognition would be a great next step. However, due to the project's time constraints, these could not be implemented.

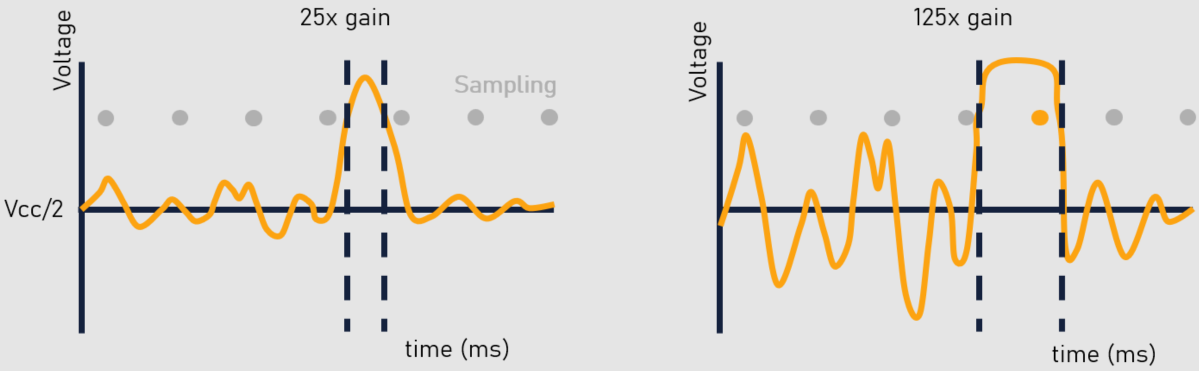

Figure 57 The effect of increasing gain on the sound signal and noise detection.

6.3 Interpretation and Decision of the Symbiote

Again, the full implementation can be found in (Rozendaal, 2025) in the chapter Interpretation and decision. The other report focuses mainly on the technical implementation, but let us focus on the reasons why we implement it in a certain way. This section discusses some of the concepts used in decision-making.

6.3.1 Human Emotions

In the final decision-making model, the symbiote does not use emotion. This is due to two reasons discussed below. However, it is recognized that it could play an important role in future research on interactions between the symbiote and humans. It could be a great expansion of the perceptive repertoire of the symbiote.

Performance of emotion detection

Unfortunately, the emotion detection models struggle in real-life situations and have an accuracy on test sets of around 66% (Singh, 2024). This is due to many reasons, but mainly has to do with the training set of the neural network. This set is heavily biased towards positive feelings, where it has 10x more pictures of happy faces than disgusted faces (Kaggle, 2013). Furthermore, many of the FACS markers used are barely visible with bad lighting, bad face detection, or angled faces.

Emotion in Less Complex Animals

Arthropods and other less complex animals can still respond to their surroundings, even though they cannot grasp the spectrum of human emotions. Small mammals or rodents presumably cannot read human emotions well. However, these animals respond to different, less complex signals of their surroundings.

6.3.2 Dominance and Intimidation

Two important concepts within the animal kingdom are dominance and intimidation. These go hand in hand and depend on your reference frame. **Dominance is a subjective measure that determines who is controlling the situation**. Your dominance level can be changed by how intimidating you are. Factors controlling this are:

- **The face and body size** of the detected people, as this gives an estimation of how close they are. A closer person is more intimidating than one further away.
- **The number of people**, where a higher number of people is perceived as intimidating and reduces the dominance of the symbiote.

- **The height** of the detected person, the higher someone is, the more intimidating they are.
- **Movement** towards the symbiote is perceived as intimidating, where a closer person has to move slower than someone further away to be perceived as non-threatening.

6.3.3 Attention

Another important factor of interactions is attention. We already briefly touched upon this in previous sections. During the explorative test, attention was one of the main feedback points. If it gives no attention to you as a person, you do not know if it notices you. However, how can we show that we are giving attention to someone?

Visual Attention

Visually showing attention can be achieved by looking at someone, just like humans do. This was the reason for adding pupils and the white part of the eye. Now, when the symbiote looks at someone, it is clear. The person whom the symbiote will look at is determined hierarchically. First, it looks if there is a head; if so, it looks at the closest head. As mentioned before, this also assures that the symbiote looks at people who are also looking at it. If there are no faces, it looks for the closest body and looks at the top of the body (roughly where the face is). If no one is there, it looks around the room at random intervals, at a speed that depends on the emotional state it is in.

Auditory Attention

People tend to look for loud sounds. They scare us and make us lose attention from what was happening, and attract our attention elsewhere. If a sound surpasses the preset threshold in loudness, then the symbiote responds to this.

6.3.4 Symbiote Emotions and States

The symbiote's emotions and states are derived from dog emotions. These are emotions humans are well-equipped to read. However, it is noted that this skill differs from human to human and is also animal-dependent. For example, someone might be good with dogs but terrible with cats.

Expressive States

The symbiote can show six emotions and has a sleep state. Static positions of these emotions are shown in Figure 58. All emotions show movement and use the concept of attention, and look at the closest person. The speed and accelerations are also state-dependent. These can best be seen in the video that accompanies this document in the DUT repository. In short, it could be summarized as: The closer a person is, the more stressed and fast-moving the symbiote. Furthermore, the ranges of these motions are also defined. The combination of these aspects makes the expressive emotion.

Transitional States

Besides the expressive states, there are three transitional states. These are going to sleep, waking up, and waking up fast. The latter is used when the symbiote is scared awake.

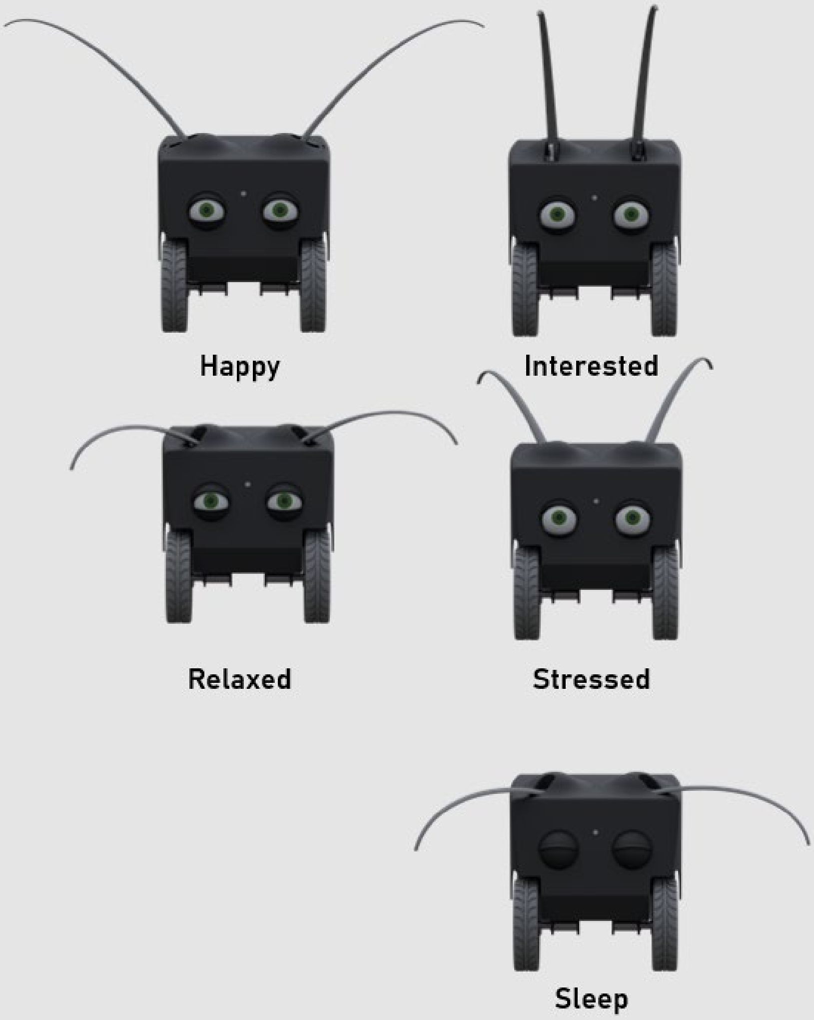

Figure 58 The possible emotional states of the symbiote

6.3.5 The Decision

The final decision on how to respond depends on the emotional state you are currently in. When you are scared, you might get more scared when someone approaches you, but when you are happy, it might be seen as a more pleasant experience. However, that is not the only thing that is important when deciding how to respond.

Character and Personality

Your character and personality are integral parts of you as a person. However, other people also attribute a personality depending on how you respond to certain situations. Some friends might say you are courageous, whilst your BMX friend might think you are not. **As designers, we can choose a personality for the robot and steer people's perception, but we cannot choose how they perceive the robot.** Because the symbiote is new, people will have to get used to it. Making it a scared robot rather than too assertive seems like a safe option. However, exploring more characters would be interesting, especially when these robots would be used to fulfill different roles.

Making a Decision Using Finite State Machines

The decision-making machine is a Finite State Machine (FSM). This was chosen because it uses the current state as information, only functions on inputs, and is thus easy to understand. This creates a platform from which new tests and behaviors can be created. Instead of using neural networks and working with a black box, all information is known and understood. The implemented FSM is shown in Figure 59.

For the full implementation, see the chapter decision in (Rozendaal, 2025). But let us explain the symbols

- (S) Sound level exceeds a predefined threshold.
- (Ts) The current state duration timer exceeds its threshold.
- (Tp) Elapsed time since no individuals have been detected.
- (P) Presence of at least one detected person; !P indicates no one is present.
- (#B) Number of detected bodies (assumes no faces were detected); B indicates #B>0
- (#F) Number of detected faces; F indicates #F>0.
- (Bs) Body size.
- (Fs) Face size.
- (ΔBs) Temporal change in detected body size.
- (ΔFs) Temporal change in detected face size.
- (H) Estimated height of the closest detected face.

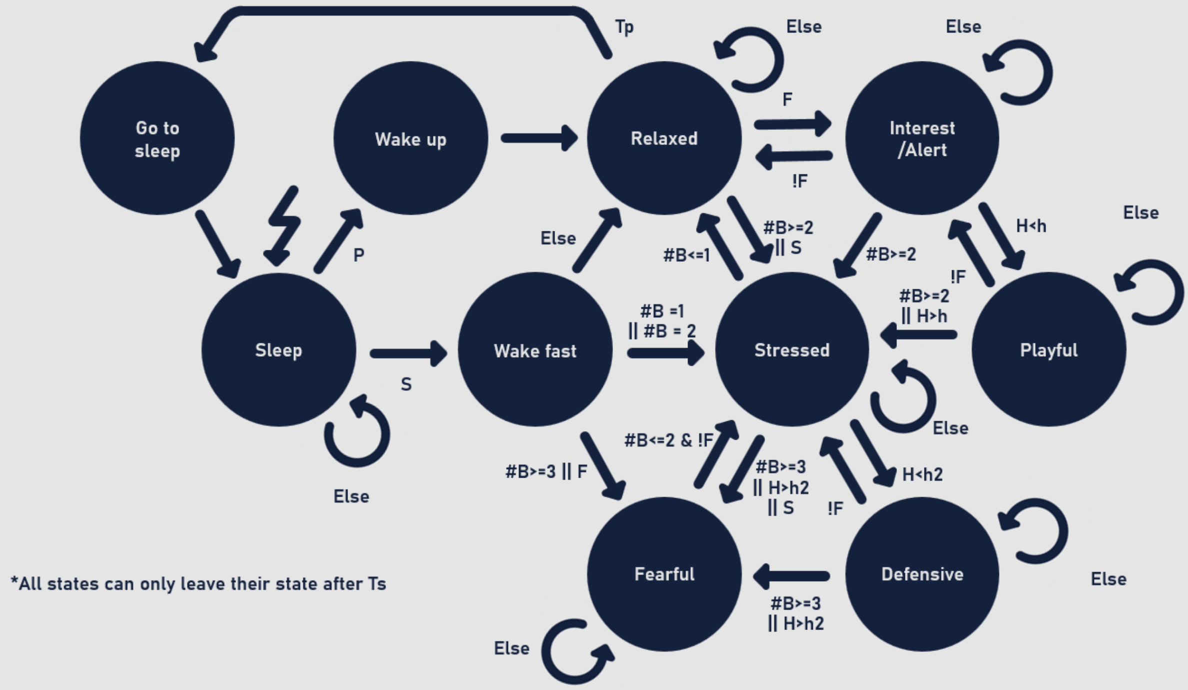

Figure 59 The Finite State Machine of the behavior of the symbiote, with the circles showing the states of the symbiote, the arrows showing the transitions, and the text showing the transitional conditions

6.4 Outputs

The outputs are the expressed emotions of the symbiote. **It is important to mention that the expressed emotion is not necessarily the perceived emotion. This is the topic of the testing and validation chapter**. For now, let us describe what the emotions were intended to be. However, first, let us make some final remarks on movements.

6.4.1 Movement

When it comes to expressing emotions through a robot, movement plays an important role. One of the most important principles is that the robot should **always be moving**, even when it is in an idle or resting state (Levillain, 2017). A completely still robot can feel lifeless or unresponsive, which breaks the illusion of personality. Even small, subtle movements, like the gentle sway of the antennae, help in making it feel alive.

The speed of movement tells a lot about the robot's emotional state. Slow, smooth motions usually communicate a relaxed state, while fast, sharp movements might indicate fear, excitement, or surprise. For example, when the symbiote wakes up, it moves slowly because it is calm and relaxed. But if it jerks awake because of a loud noise, the speed of that movement instantly signals a kind of startled fear.

Movement range also adds another layer of meaning. Smaller, confined movements tend to feel cautious, shy, or reserved, while larger, more open gestures can look confident or expressive. When stressed, the symbiote moves in a tighter range, appearing tense. But when it is playful, it happily swings its antennae.

Then there is **randomness** in movements, which is essential for avoiding a robotic, repetitive feel. If the robot always moves in the same way at the same intervals, it quickly becomes predictable and mechanical. Adding a small quantity of variation in timing, direction, or speed gives the impression of realism. It mimics the natural unpredictability of living creatures, who are never perfectly symmetrical or rhythmic in how they move.

Together, these elements create a believable and emotional behavior. They help the robot "feel" more alive and relatable, making its reactions more intuitive for humans to read and connect with.

6.4.2 The Expressions

Now that we have gone over everything, let us take a look at the emotions in the FSM. The detailed implementation is in the decision chapter of (Rozendaal, 2025). Here, the states will be discussed in an expressive and interactive light.

First, there is the **Sleep** state. This is the robot's default mode when it is idle. It remains asleep as long as nothing triggers it to wake up. While asleep, it slowly, at random intervals, moves the antennae. The symbiote can wake up in two ways: if it detects a person visually, it wakes up slowly, simulating how animals sense vibrations in the ground, or if it hears a loud sound, it wakes up quickly, similar to how something might scare you awake.

When it wakes up, it can go into **Wake Up** or **Wake Fast**. If it detects a person nearby (P), it wakes up calmly and starts to get more aware of the environment. If there is a sudden sound, it enters a more alert state with a heightened state of awareness. From here, it can move into different emotional states depending on what it senses. If someone is too close or if there are many people around, it becomes fearful. If there are just one or two people, it may get a bit anxious (Stressed), or if no one is around, it stays calm (Relaxed).

Relaxed is the calm state the symbiote falls into after it wakes up. As long as no one is there, it stays relaxed, but if it sees a face, it becomes more interested and alert. If there are multiple people nearby or if there is a loud noise, it may get stressed. Moreover, if it does not see anyone for a while, it returns to the go-to-sleep state.

In **Go to Sleep**, the robot slowly shuts down, mimicking how it would go into a resting state and eventually back to Sleep. It is like the robot is winding down and taking a break.

Next is **Interest/Alert**, where the robot is paying attention to its surroundings. If it does not perceive a threat (like if the closest person is not intimidating or too tall), it becomes **Playful**, showing a friendly and open side. But if the situation gets more serious with loud sounds or more people, the symbiote may feel stressed again. If the person they are interested in goes back, the symbiote starts to relax again.

In the **Playful** state, the symbiote is more socially interactive, responding well to its environment and being engaging. But if the visual cues disappear, it goes back to Interest/Alert. If things get crowded or if the symbiote gets startled, it might feel stressed.

Then there is **Stressed**, the symbiote is on edge. It is in a heightened state, ready to react to changes. If the environment becomes overwhelming, when there are many people or loud sounds, the symbiote gets fearful. If things calm down, it can go back to being relaxed. However, if there is just one person who comes too close, the symbiote can get defensive.

Fearful is the most reactive state. The symbiote feels threatened and is easily triggered into this state. The only way out of this is to calm down through the stressed state, but only if there are no immediate threats.

Finally, there is the **Defensive** state, where it is intimidated but the opponent is less dominant than itself. If things calm down or the threat disappears, the symbiote can go back to being stressed or even retreat into fearful if the situation changes and it feels cornered again.

6.5 On Interactions

We have discussed all four parts of the interaction. However, to create intuitive and engaging interactions, there are a few more concepts we need to discuss to finalize this chapter.

Response Time

The response time of the symbiote is important for the perceived realism. Choppy movement can result in unrealistic behavior. Furthermore, the time it takes to detect someone and give that person attention (also called reaction time) determines if any real-time interaction is possible. The explorative test also showed that the maximum response time should be 100 milliseconds. **This means the total cycle for the symbiote of detection, decision, and expression should be functioning at 10 Hz.**

Adding Routines

More routines like blinking could help in creating an even better and more realistic interaction. **Adding winks, eye rolls, room scans, and similar actions helps create a better responsive vocabulary for the symbiote**.

Remarks on the Uncanny Valley

Lastly, it is important when making changes to consider the uncanny valley. As discussed earlier, when robots start to look and act like humans, they should avoid this valley. It is better to remain further away from human likeness than to get too close. This is also one of the reasons for taking **inspiration from animals more than humans.**

7 Technical Design

This chapter describes the technical design of the symbiote. This report mainly discusses the mechanical design, whereas the other report mainly discusses the electrical and software design (Rozendaal, 2025). The design decisions made in the ideation chapter are used to create the technical design. We will start with all the subsystems of the symbiote and follow with a short discussion on the host. Then we will finalize it with the integration and fabrication. A manual on the assembly will be available on the GitHub page mentioned in Appendix F.

7.1 Symbiote

The mechanical design of the symbiote is split into five parts. The eyes and eyelids are separate mechanisms and will be treated as such. After that, the antennae, the frame, and the housing. The movements are difficult to convey and are better shown in the video accompanying this document.

7.1.1 Eyes

Let us start with the most important system, the eyes. The technical drawings are shown in Figure 60. The top view nicely shows all the x-axis hinges (1) connected by a rigid bar that moves when the x-axis servo turns. The eyes (6) themselves lie in the eye sockets, and together they function as a ball joint. This means the eyes can freely rotate in the eye sockets, both in the x and y directions. The y-axis servo (4) lifts the whole mechanism. Because both eyes are mechanically linked using a rigid bar, only two servos are required. A render of the eye mechanism is shown in Figure 61. It more clearly shows how the eyes look and how the iris and pupil are visible on the eye. All parts are 3D printed and connected using screws an inserts except the iris and pupil. They are glued to the eyes. This design also utilizes the servo arms that come with the servos.

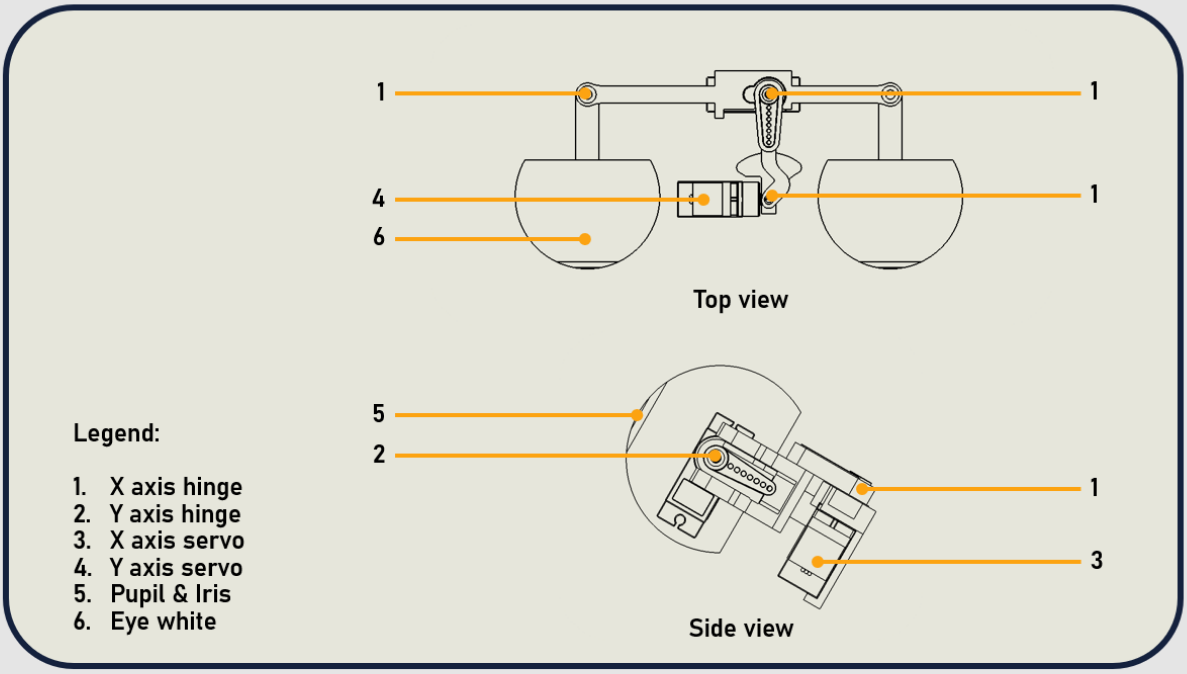

Figure 60 Technical drawing of the eye mechanism

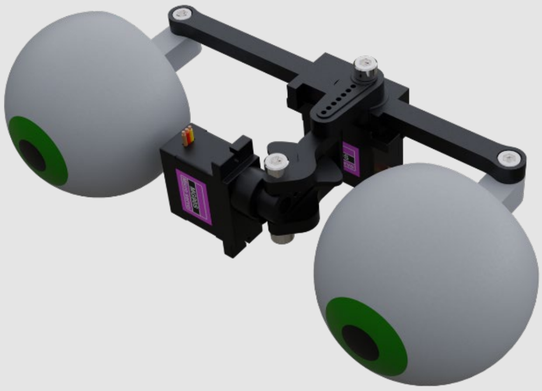

Figure 61: Render of an isometric view of the eye mechanism

7.1.2 Eyelids

The eyelid mechanism sits around the eyes. One of the two mechanisms is shown in Figure 62. The eyelids (2 and 3) rest inside the eye socket. Both eyelids have a handle (1) that functions as a hinge, which is connected through a steel wire (5) to the servo (7). The steel wire was chosen because of its flexibility. This allowed for less exact measurements. However, it is recommended that this be changed in the next version. The servo uses an arm (8) to push and pull the metal wire that rotates the eyelids from open to closed and vice versa (as seen in Figure 64). The servo is attached to a holder (9) that is connected to the baseplate of the frame. A render of this mechanism is shown in Figure 63. Here, the 30-degree angle of the mechanism is clearly visible. A mirrored version of this mechanism is used for the other eyelid.

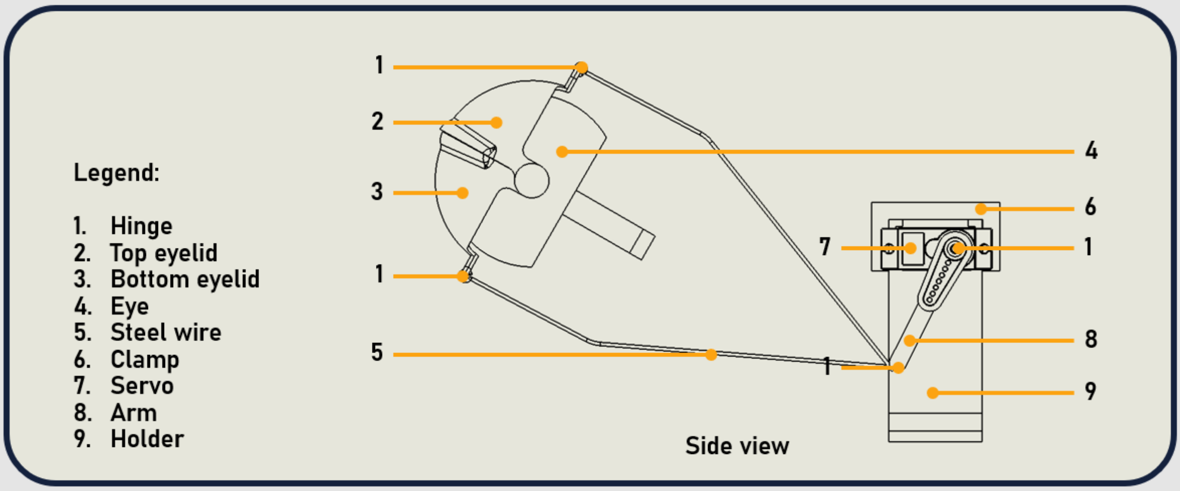

Figure 62 Technical drawing of the eyelid mechanism

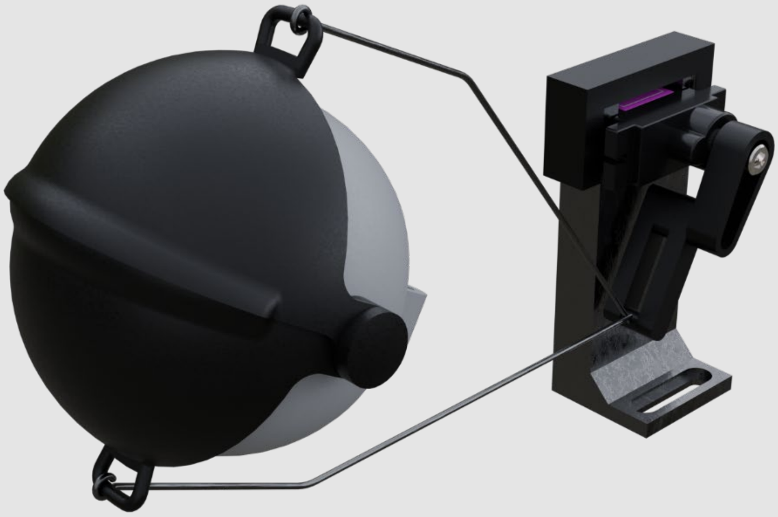

Figure 63: Render of an isometric view of the eyelid mechanism

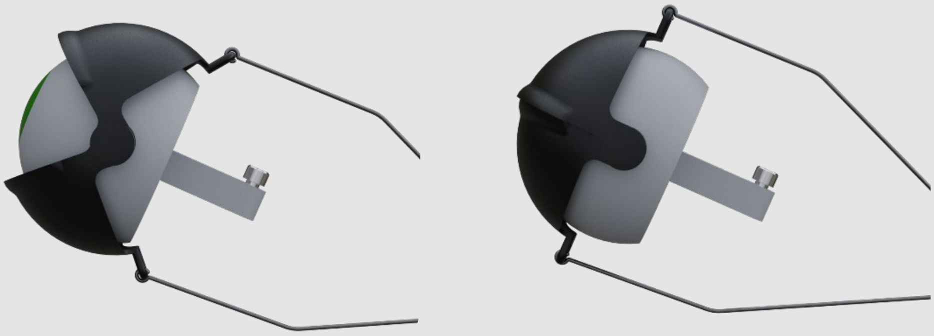

Figure 64 Render of a side view of the eyelids showing the open and closed position

7.1.3 Antennae

The Antenna is controlled by and secured to the antenna holder. One such holder is shown in Figure 65. The holder has a raised wall where the cap is secured, which is better visible in Figure 66. It also shows what the antenna looks like. The antenna is bent into shape when it comes out of the 3D printer. It is made of flexible TPU material. The antenna holder rotates in its entirety, which means the cables need a place to pass. This is the function of the semicircle hole (2). The mounting pillars (5) are used to secure the large servo (3) that holds the antenna (8) and performs its y-axis rotation. The small servo (4) is attached to a hole in the bottom of the holder and is attached to the frame. This way, it can rotate the entire holder around its x-axis. This is also the reason for the circular shape.

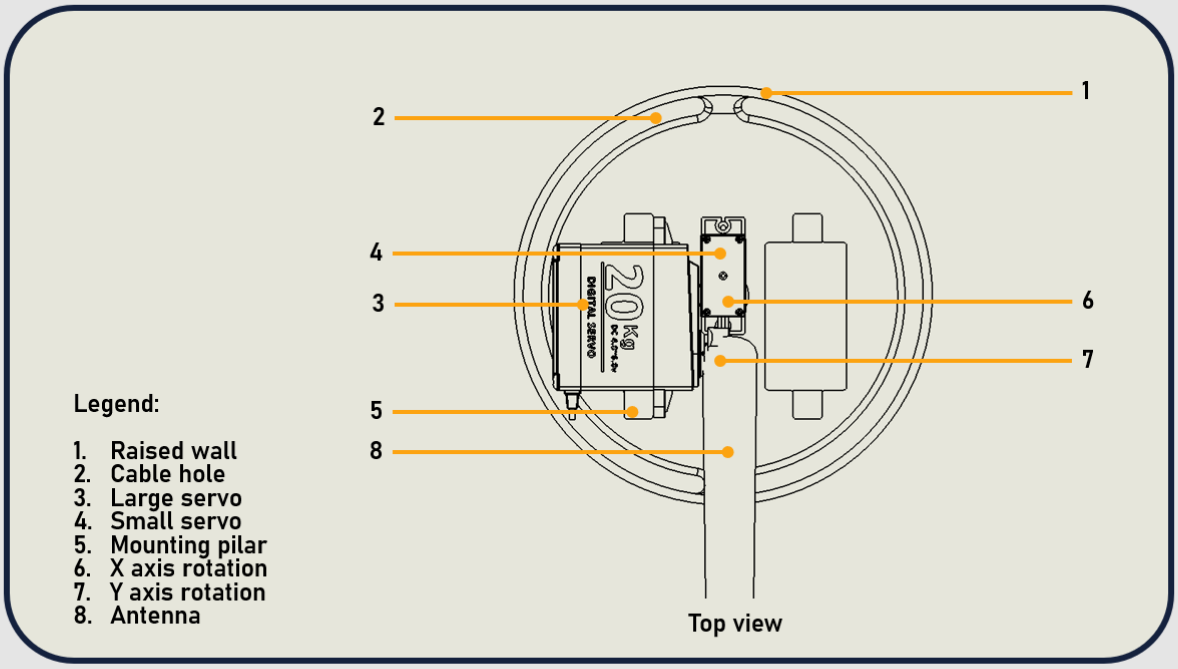

Figure 65 Technical drawing of the antenna mechanism

Figure 66 Render of and an isometric view of the antenna holder with (left) and without cap (right)

7.1.4 Frame

The frame holds the three appendages and is the structural base of the symbiote. Figure 67 shows the technical drawings of the frame. **The flat bottom plate (10) serves as a mounting place for the host. This way, it can be connected to any host with a flat top using the motor connection holes (1).** The top of the frame has two connection points for the antennae (2) and two larger holes for the cables to pass through (4). The frame consists of three parts that are connected using screws and inserts (3 & 9). On the front, it has the camera mount (6) and the eye mechanism servo mount. The bottom plate also has insert holes to connect the eyelid mechanism and other components.

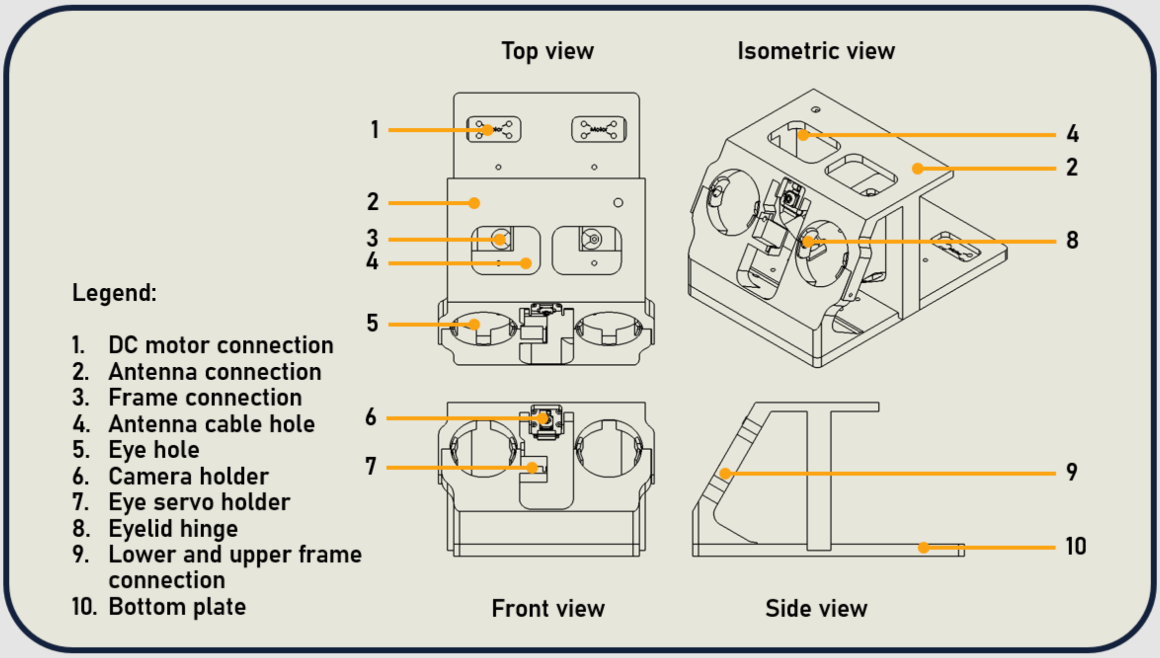

Figure 67 Technical drawing of the frame of the symbiote

7.1.5 Housing

The housing covers all the internal components. The technical drawings are shown in Figure 68. It shows how the antenna modules fit in the housing (1) and how the camera is covered (2). At the 30-degree slanted front, it shows the holes for the eyes. For this host, an open-wheel section needed to be created. The housing rests on top of the frame (see Figure 69) and is held in place by the antenna holders. For future versions, it might be good to secure the housing directly to the base. This is especially important when altering the weight distribution.

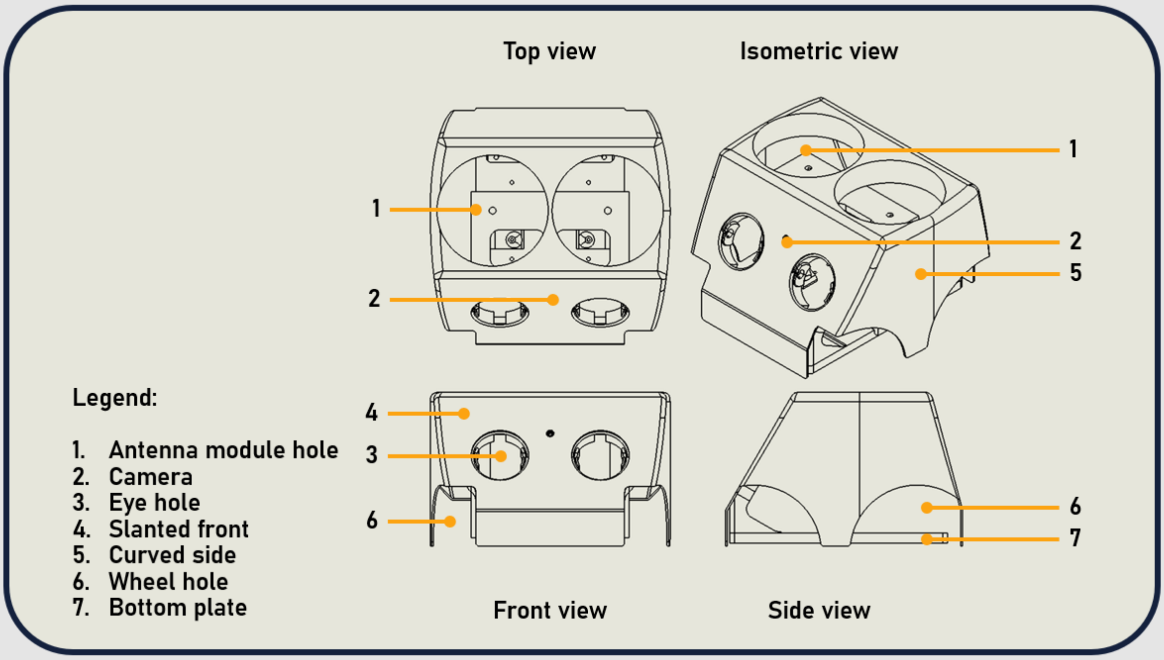

Figure 68 Technical drawing of the Housing of the symbiote

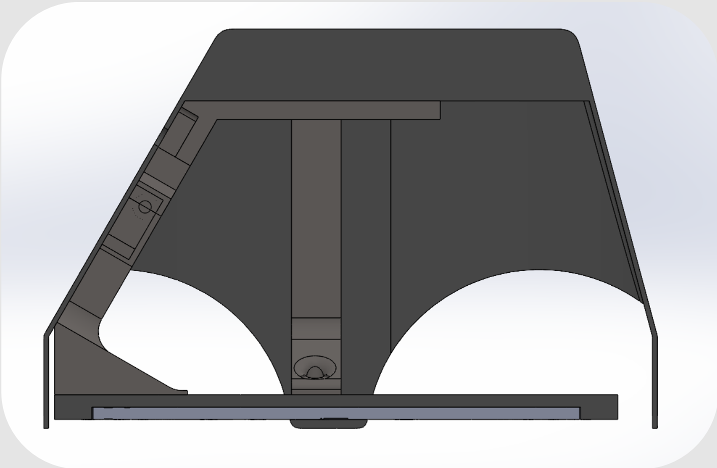

Figure 69 Render of the cross-section side view showing that the body rests on the frame

7.2 Host

Figure 70 shows a render of the host used in this project. This minimal host is to test the symbiote (locomotion and power). It consists of a wooden frame with four motors, motor holders, and wheels. The hosts frame is connected to the symbiotes frame using screws. The wheels are made out of flexible TPU materials to absorb most of the shock. Lastly, the power bank is connected to the bottom of the frame to keep the center of mass low and in the middle. This also makes sense from the point of view of the symbiote, as the host provides the power.

Figure 70 Render of the host body used for the case study

7.3 Integration

Now that all the sub-systems and the host have been discussed, the integration can be described. Figure 71 shows the technical drawings of all the sub-systems except the housing. In this figure, all the electronics locations are marked. It shows the Arduino close to both motor drivers and the Raspberry Pi. The Raspberry Pi is placed on top, close to the camera, so that the ribbon cable can be connected. Another reason is that it requires cooling. The motor locations are shown in Figure 72. Here you can see the two large servos and all six small servos. Lastly, the four DC motors are directly connected to the four wheels.

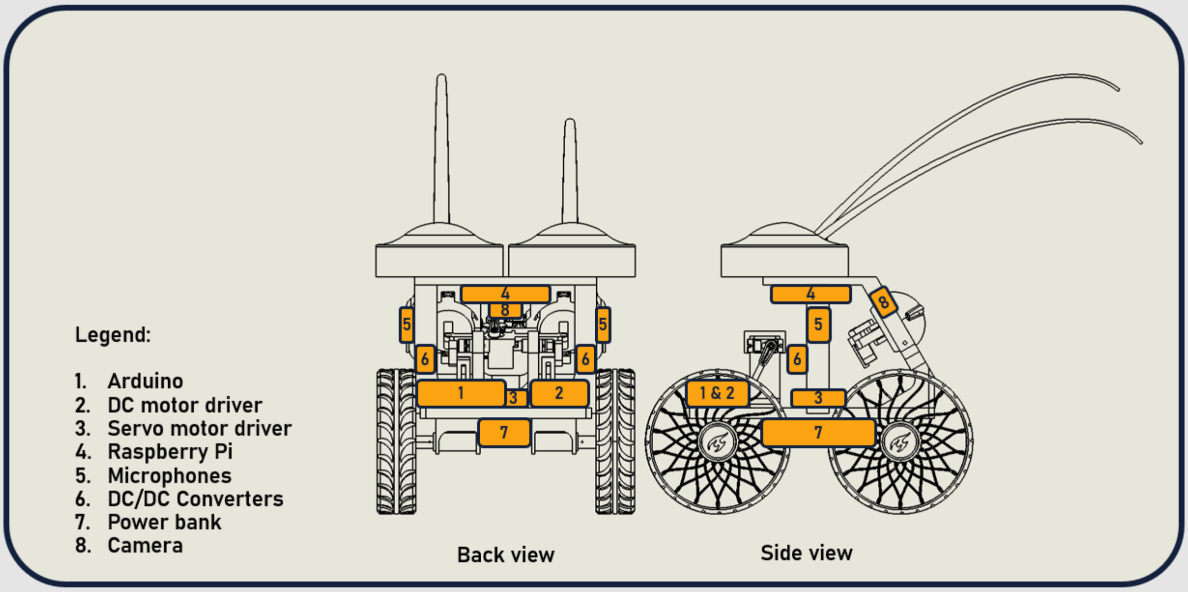

Figure 71 Technical drawing of the robot showing the location of the electronics

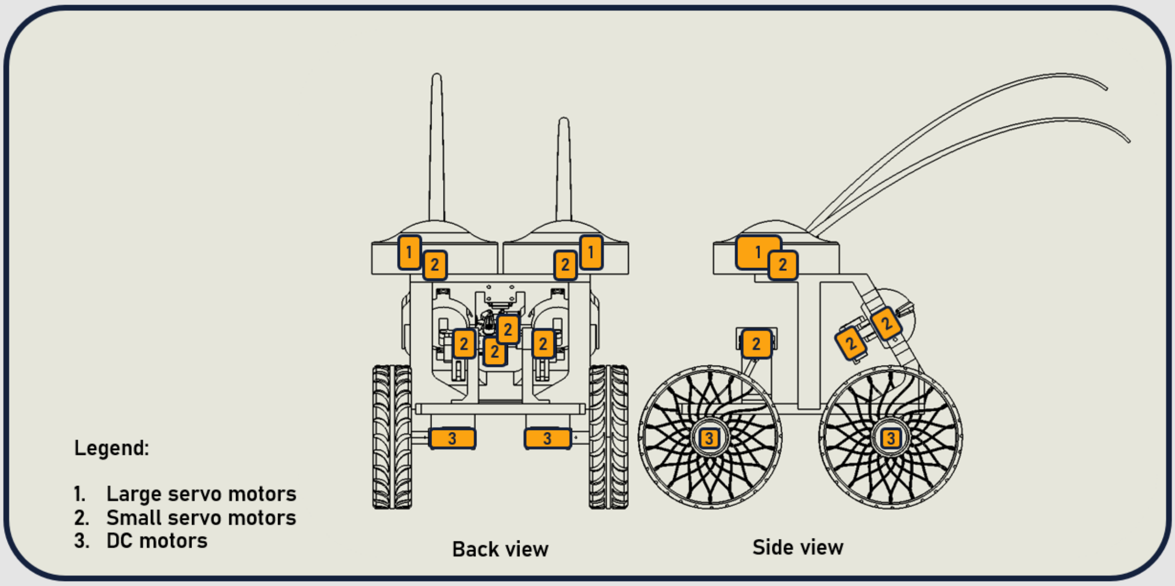

Figure 72 Technical drawing of the robot showing the location of the motors

7.4 Production

It has already been mentioned that the symbiote is made of 3D printed materials. This is done as it allows for easy reproduction and later modifications. This way, people who want to reproduce it can make it at home, work, or school as long as a 3D printer is available. The other materials, screws, inserts and steel wire are all widely available. Similarly, the electronics are all standard components that can be bought at large electronics providers.

Because it only uses standard M2 and M3 screws and inserts, the symbiote can be built using a screwdriver and a soldering iron. It requires very little skill or domain knowledge to put together. A complete guide will also be made available on the GitHub page mentioned in Appendix F. For the construction no soldering is required when screw connectors are used. The only reason for the soldering iron is to push in the inserts.

A good side effect of this manufacturing method is that it is also easy to customize the visual aspect of the robot. Some color suggestions can be seen in Figure 73. Eyes or housing of different colors could have different characters. Blue being shy, orange more assertive, and pink happier.

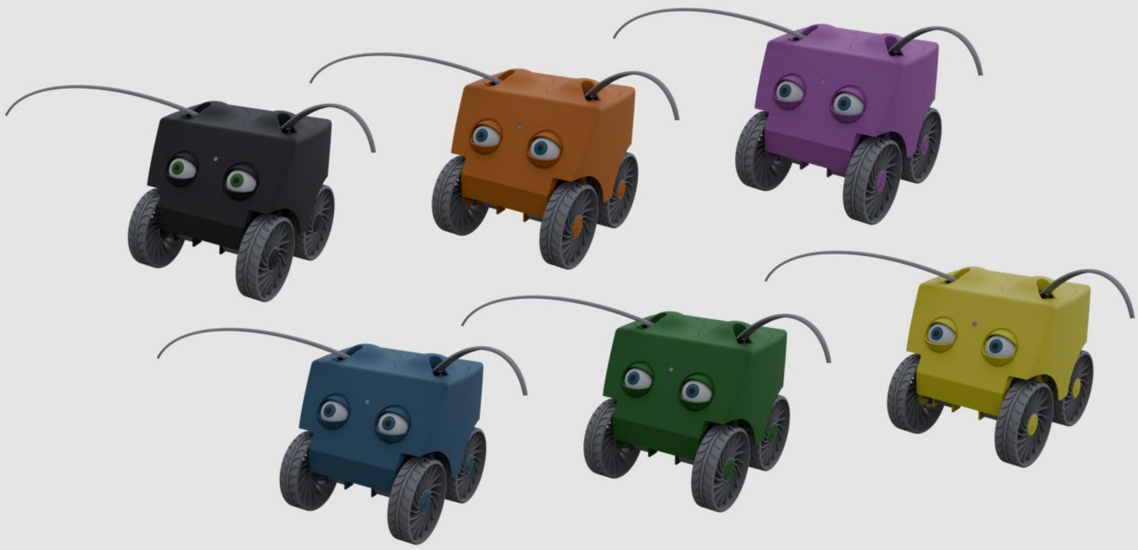

Figure 73 Renders of the robot in different colors

8 Analyses

This chapter contains all the analyses performed on the symbiote, host, and robot as a whole. The analysis regarding power, responsiveness, sensors, and actuators stems from the other report (Rozendaal, 2025). However, all will be mentioned here, as they are important to determine the functioning and to answer the research questions later. The interactions and emotions are discussed in the next chapter, where they are tested, validated, and discussed.

8.1 Cost

The BOM can be found in Appendix G. This shows the cost, quantity, retailer, and purchasing link of all components used. Using the BoM, a purchase list can be created by entering the number of robots that are to be made.

The cost of one robot depends not only on the purchased components but also on the number of robots. Making more robots decreases the unit price, even without changing to production methods that scale. This is due to delivery costs, packaging quantities, one-time purchase items, and filament remainders. Using this, a calculation is made for the prices of one robot compared to the price per robot in bulk (incl. Dutch taxes of 21%). Table 2 shows the cost of one robot compared to the bulk price per robot. It also splits up the cost for the symbiote and host and **shows that the symbiote benefits most from bulk purchases, making it perfectly suitable for swarming robots.**

Table 2 Cost of a single robot, symbiote, and host in low volume and in bulk

Cost Metric	Total	Symbiote	Host
Price one robot (euros)	€ 967.22	€ 654.41	€ 312.81
Bulk Price/Robot (euros)	€ 658.15	€ 345.35	€ 312.80

8.2 Production Time & Weight

The weight of the symbiote is important because the host should be able to carry it around. Next to this, for a larger number of symbiotes, the print time required is also important. If only a few printers are available, this could hamper production. No print optimizations were performed. However, analysis on print duration, filament usage, and filament loss was performed and shown in Table 3. **For the symbiote, it shows 42 hours of print time, 1.5 kg of filament, 0.2 kg of filament loss, and a total weight of 1.5 kg**. Filament weights and print times are retrieved from the Bambulab slicer, whereas the final weights are obtained through scale measurements.

The retailers can be found in the BOM. It shows that all of the materials are bought from a small group of large retailers with local distribution centers. This reduces risks in the availability of the products. The selection of all electronics components is performed in the ES report, but also adheres to these rules.

Table 3 Robot fabrication time, filament use, filament loss, and total weight for both symbiote and host

Fabrication Metric	Total	Symbiote	Host
Print time (h)	69.6	42.2	27.5
Filament usage total (kg)	2.21	1.48	0.73
Filament usage robot (kg)	1.92	1.29	0.64
Filament loss (kg)	0.29	0.19	0.09
Number of prints	53	29	24
Weight (g)	2638	1508	1130

8.3 Power & Electronics

The electronics schematic can be found in Appendix F. After connecting the electronics, a USB-C power measurement tool was used to perform power measurements. This is inserted between the power bank and the buck converters. It measures the power over time and provides an average. The results were performed on the whole robot and on the robot where the DC motor driver was disconnected (Symbiote). Table 4 shows the measured power consumption per state. It is important to mention that, except for the happy state, all other states do not use the DC motors during the state, but only upon entering it. This means the measurements do not consider this. This also explains the high power usage in the happy state compared to the others.

Using the average power consumption of 12.34 Watts and assuming every state had an equal presence, the battery life can be calculated. The effective capacity of the power bank is 100Wh. Dividing this by 12.34 Watts **gives a battery life of 8.1 hours.**

Table 4 Power usage in different states for the robot, symbiote, and host

Power usage	Total (W)	Symbiote (W)	Host (W)
Sleep	10.9	10.7	0.2
Relaxed	11.5	11.2	0.3
Playful	16.7	11.9	4.8
Alert/Interested	11.3	11.2	0.1
Stressed	11.7	11.6	0.1
Fearful	12.5	12.3	0.2
Defensive	11.8	11.6	0.2
Average	**12.34**	**11.50**	**0.84**

8.4 Responsiveness

The ES report discusses responsiveness in more depth. In the current symbiote, the Raspberry Pi is the performance bottleneck. As mentioned before, a minimum FPS of 10 is needed to obtain valuable interactions and create smooth movements. **The symbiote has an average of FPS of 13.5 and a worst case of 9.71.** This is sufficiently close to 10 FPS.

8.5 Sensor & Actuator Specifications

Table 5 shows the visual performance metrics for all three detection types and the final design of the symbiote. The distances were measured with the robot on the floor and a Caucasian male of average Dutch height (1.80 meters) standing up straight. This would be a realistic scenario for the robot in its use. The minimum distance for face detection is greater than for body detection because, at close range, the face may fall outside the camera's field of view, whereas body detection still works by recognizing the lower part of the body. For the number of detections, multiple people were put within the distance range, and a minimum of three people were tested. Emotion detection was only tested on the closest detected face.

Table 6 shows the microphone specifications, as used in the symbiote. The two microphones on the symbiote can detect when a sound reaches each microphone. If a sound comes from one side, it will reach the closer microphone slightly earlier than the farther one. By measuring this small difference in arrival time (called the **Time Difference of Arrival**, or TDoA), the robot can estimate the direction the sound came from. This is useful when looking for the source of a loud sound.

However, it must be stated that the current sampling frequency of the Arduino is insufficient for this purpose, and performing this calculation requires an extra dedicated processor. Furthermore, the full range of human speech is within the detectable band. The trigger value for loud sounds is set around 70 dB, which is above a loud conversation close to the robot. **This means the robot will not trigger due to regular conversations, but will trigger from a loud clap or shout.**

Table 5 Performance metrics for the face, body, and emotion detection, and the metrics for the symbiote (the combined best of the implemented body and face recognition)

Recognition	Face	Body	Emotion	Symbiote
Distance max (m)	1.16	4.95	1.16	4.95
Distance min (m)	0.55	0.33	0.55	0.33
Number of detections	>3	>3	1	>3
FPS	88.1	15.4	11.64	13.51
Viewing angle (degrees)	60	60	60	60

Table 6 Microphone specifications used for the symbiote

Specifications	Value
Number of microphones	2
Trigger value (dB)	70
Frequency min (Hz)	20
Frequency max (Hz)	20000
Sampling frequency (Hz)	250

The movements of the symbiote can be split into three. The first is the antennae. The antennae can move independently (asynchronously) from each other. The movements are very similar to how insects use their antennae. The vertical position of both antennae has a range of 90 degrees, and the horizontal movements have a range of 180 degrees.

The eye and eyelid movements are synchronous. This means both eyes have the same angle, and so do the eyelids. However, the eyelids are not physically linked, meaning they could move asynchronously.

A summarization of these movements is shown in Table 7. It shows the degrees of freedom and the angle range per degree of freedom for all three appendages. These movements are then used to express the emotions.

Table 7 Degrees of freedom and movement range for the three appendages of the symbiote.

Appendix	Antennae	Eyes	Eyelids
Degrees of freedom	2	2	1
Angle Range vertical (°)	90	60	60
Angle Range horizontal (°)	180	60	-

9 Testing & Validation

This chapter discusses the testing and validation of the emotional expression of the symbiote. It discusses the method, test setup, and results. The test was created based on the ideation phase and the suggested improvements in the exploration phase.

9.1 Method

The test is divided into four phases. These phases are:

- Phase 0: Formalities
  - Read the opening statement and explain what the test will contain.
  - Mention that any photos will be anonymous and that they have two weeks to revoke their data. If not revoked, the data will be aggregated.
  - Signing the informed consent form
- Phase 1: Context video
  - Explain that the participant will be viewing four interactions with the symbiote to learn through context. These videos are schematically shown in Figure 74.
  - Show the context videos 1 – 4 in a random order to the participant.
  - If they want to revisit a video, that is allowed.

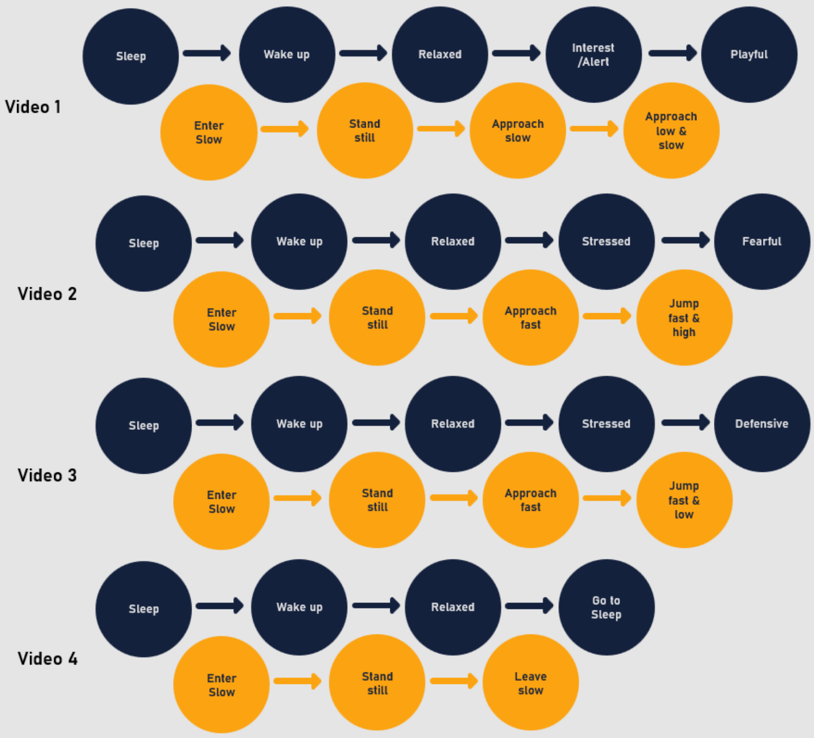

Figure 74 Emotional states are shown in order from left to right in all four interaction videos, with the robots emotions in blue and the humans actions in orange.

- Phase 2: Emotion reading
  - Give the participant the answer sheet (the same as in the explorative test) and explain how to fill it in. Also, ask if they have any questions regarding the emotions.
  - Go through all emotions one by one (first relaxed, and then in a random order) without filling in the answer sheet. This is done to give the participant an understanding of all the possible emotions.

    - Go through all emotions again one by one (In the same order as before) and let the participant fill in the answer sheet.
    - The participant can revisit emotions.
- Phase 3: Discussion
    - Discuss the answers with the participant.
    - If desired, show the participant the intended emotions.

9.2 Test Setup

Phases 0 and 1 take place in front of a laptop screen at a desk. Phases 2 and 3 take place in a room with an open middle. The participant is asked to remain in a box of 3x3 meters, about 0.5 meters away from the robot. This not only allows for a safe distance from the robot but also allows the robot to better perceive the human (a face is detected from this distance). Lastly, this distance means that the robot can safely drive towards the participant when interested or defensive.

The participant is free to move around in this 3x3 area. This way, they can experience the eye following and have a more realistic interaction. This also allows for more interesting conversations during phase 3, where an open discussion is possible.

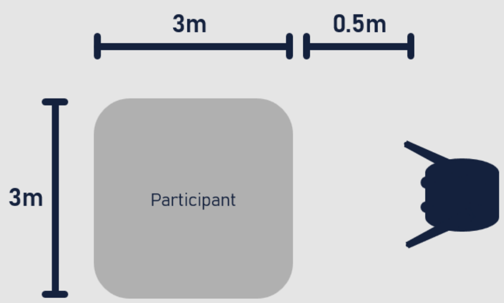

Figure 75 Test setup for phase 2 of the test showing the participant area compared to the symbiote

9.3 Results

Figure 76 shows the test results on 20 participants. For every emotion that was shown (actual emotions), the participants could give a score from 1 through 7 to all the emotions (perceived emotions). This means that when an emotion is shown, the participant could give a score of 1 for all emotions that they think are not relevant, they could give a score of 7 for all emotions if they think all are relevant, or they could score anywhere in between.

To better interpret the scores, they were normalized and organized into a matrix. This allows two key aspects of performance to be assessed. **First, detectability: how well an emotion is recognized when it is actually shown (analyzed by looking across each row). Second, distinguishability: how rarely an emotion is mistakenly identified when other emotions are shown (analyzed by looking down each column).**

If the design were perfect and all participants were correct, the scores would show 1 in the diagonal and 0 in the other squares. However, this is never the case. For each emotion, the columns and rows received conditional formatting where more orange is a better score. The scores are in the order relaxed, playful, alert/interested, stressed, fearful, defensive.

Actual \ Perceived	Relaxed	Playful	Alert/Interested	Stressed	Fearful	Defensive
Relaxed	0.73	0.27	0.48	0.13	0.13	0.15
Playful	0.33	0.62	0.53	0.34	0.23	0.23
Alert/Interested	0.28	0.43	0.71	0.36	0.32	0.32
Stressed	0.10	0.16	0.46	0.73	0.69	0.37
Fearful	0.01	0.03	0.48	0.88	0.98	0.34
Defensive	0.13	0.28	0.55	0.52	0.38	0.79

Actual \ Perceived	Relaxed	Playful	Alert/Interested	Stressed	Fearful	Defensive
Relaxed	0.73	0.27	0.48	0.13	0.13	0.15
Playful	0.33	0.62	0.53	0.34	0.23	0.23
Alert/Interested	0.28	0.43	0.71	0.36	0.32	0.32
Stressed	0.10	0.16	0.46	0.73	0.69	0.37
Fearful	0.01	0.03	0.48	0.88	0.98	0.34
Defensive	0.13	0.28	0.55	0.52	0.38	0.79

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Relaxed	0.73	0.27	0.48	0.13	0.13	0.15
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Alert/Interested	0.28	0.43	0.71	0.36	0.32	0.32
Stressed	0.10	0.16	0.46	0.73	0.69	0.37
Fearful	0.01	0.03	0.48	0.88	0.98	0.34
Defensive	0.13	0.28	0.55	0.52	0.38	0.79

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Relaxed	0.73	0.27	0.48	0.13	0.13	0.15
Playful	0.33	0.62	0.53	0.34	0.23	0.23
Alert/Interested	0.28	0.43	0.71	0.36	0.32	0.32
Stressed	0.10	0.16	0.46	0.73	0.69	0.37
Fearful	0.01	0.03	0.48	0.88	0.98	0.34
Defensive	0.13	0.28	0.55	0.52	0.38	0.79

Actual \ Perceived	Relaxed	Playful	Alert/Interested	Stressed	Fearful	Defensive
Relaxed	0.73	0.27	0.48	0.13	0.13	0.15
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Alert/Interested	0.28	0.43	0.71	0.36	0.32	0.32
Stressed	0.10	0.16	0.46	0.73	0.69	0.37
Fearful	0.01	0.03	0.48	0.88	0.98	0.34
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Playful	0.33	0.62	0.53	0.34	0.23	0.23
Alert/Interested	0.28	0.43	0.71	0.36	0.32	0.32
Stressed	0.10	0.16	0.46	0.73	0.69	0.37
Fearful	0.01	0.03	0.48	0.88	0.98	0.34
Defensive	0.13	0.28	0.55	0.52	0.38	0.79

Figure 76 Normalized test results showing the actual (intended) and the perceived emotions of (in order) relaxed, playful, alert/interested, stressed, fearful, defensive. With orange conditional coloring depending on the score.

9.4 Discussion on the Test

The emotion perception matrices present a clear visualization of how well participants were able to identify various emotional expressions when a specific target emotion is shown. Each row in the matrix represents the actual emotion presented, while each column indicates the emotion as perceived by the participants.

The emotional expression performed well in terms of detectability. The emotions *Fearful* and *Defensive* consistently demonstrated the highest recognition accuracy, with *Fearful* achieving values close to perfect identification. Similarly, *Relaxed* and *Playful* also yielded strong detectability, while *Alert/Interested* and *Stressed* performed moderately well. The scores on the diagonal of the matrices are noticeably higher than most off-diagonal scores, suggesting that, in general, **participants were able to correctly identify the displayed emotion more often than not**.

However, **distinguishability was more variable**. *Relaxed* and *Defensive* were relatively well distinguished, which means participants rarely selected them when a different emotion was shown. Other emotions, such as Playful, Stressed, and Alert/Interested, were more frequently confused with each other. **This may reflect perceptual or conceptual similarities among these emotion**s. For instance, *Playful* and *Alert/Interested* both involve elements of engagement and heightened attention, which may lead to difficulty in clearly differentiating them during perception. Similarly, *Stressed* and *Fearful* were frequently misattributed to one another, which makes sense as they perform similar functions in nature.

From a biological perspective, these patterns align with what would be expected. Emotions like *Fearful*, *Stressed*, and *Defensive* form a functional cluster associated with threat detection and avoidance. In such states, precision in distinguishing the specific type of arousal may be less critical than recognizing that some form is present. As a result, it is unsurprising that these emotions exhibit higher confusion with one another. In contrast, ***Relaxed* stands out as a low-arousal state and is well-separated from the others in both detection and distinction, suggesting it has a clear behavioral and perceptual signature.**

Interestingly, the recognition of *Playful* and *Alert/Interested* may require more nuanced cues to distinguish effectively. **These are socially complex emotions that are both positive and have moderate arousal. They often rely on context or subtle differences in expression to be differentiated. This overlap presents a challenge for human perception and distinction.**

In conclusion, **the emotion recognition system demonstrates robust performance in detecting certain core emotions, especially those with distinct biological functions like *Fearful*, *Defensive*, and *Relaxed*.** However, emotions that exist along a similar spectrum of social engagement may benefit from design enhancements that provide additional context or multimodal cues. ***Playful, Alert/Interested*, and *Stressed* exhibit higher levels of confusion and may benefit from design enhancements that provide additional context or cues**. However, in nature, nothing happens without context, which is something this test did not take into account. For future endeavors, it is advised to look at these results in context.

10 Technical Requirements

In this chapter, we will discuss the technical requirements that will be used for the ES report (Rozendaal, 2025). They are stipulated using the MoSCoW method (Miranda, 2022). This method categorizes requirements into "must have, ""should have, ""could have," and "will not have. " These mean:

- **Must have:** Non-negotiable requirements that are mandatory for a successful outcome.
- **Should have:** Important requirements that are not vital but add significant value.
- **Could have:** Requirements that are nice to have, add only small value, and are pursued if time allows.
- **Will not have:** Requirements that are out of the project's scope due to prioritization or time constraints. These will not be used in this report as the scope is already relatively broad and clearly defined.

10.1 Must-Have Requirements

The must-have requirements with reasoning are shown in Table 8. This table shows a complete overview, but some requirements deserve more attention.

M.01 through **M.04** are all robot requirements. These are needed to perform the functionalities for the case study. Here, safety checks are critical as the robot will be close to humans and interact with them.

M.05 and **M.06** are on autonomy. These requirements are important for the case study implementation. For this the robot should be fully autonomous and work on startup without significant external efforts.

M.07 through **M.12**, and **M.14** are all on sensing and interpretation. These detection requirements were determined to be necessary in the interaction design chapter. All these requirements were tested up to the requirement limits in the ES report.

Requirement **M.13** was one of the most limiting and challenging requirements in this design. Determined early on, it was one of the most difficult to obtain. This is also further discussed in the ES report.

Table 8 Must have requirements for the ES report, with the reason for implementation

Requirement	Reason
M.01: The robot must successfully finish the device safety check of TU Delft	Ensures the robot complies with institutional safety standards before being tested or deployed on TU Delft premises.
M.02: The robot must be rechargeable	Allows for repeated use. Mentioned in relation to sustainability and usability for the case study.

M.03: The robot must be able to run for at least 3 hours	Ensures sufficient operational time during deployment in the Cyber Zoo or during workshops.
M.04: The robot must be able to move around on a flat surface	To interact effectively in typical indoor environments.
M.05: The symbiote must be able to function on startup, without I/O devices, e.g., screens, keyboards, or mice	Autonomy is crucial; minimizing dependency on peripherals supports seamless and portable operation.
M.06: The symbiote must be fully autonomous except for an external power source	Ensures it can operate without user intervention when attached to a host.
M.07: The symbiote must have a camera angle of at least 60 degrees vertically and horizontally	This field of view allows for perception similar to that of humans.
M.08: The symbiote must be able to detect a human from at least 3 meters	Needed for early recognition and engagement in interactive environments.
M.09: The symbiote must be able to detect a face from 1 meter	Essential for initiating close-range human-robot interaction.
M.10: The symbiote must be able to detect at least three bodies	It supports group interaction scenarios and is critical for emotional decision-making.
M.11: The symbiote must be able to detect at least three faces	Similar to M.10.
M.12: The symbiote must be able to discriminate the closest person	Critical for targeting attention and responses to the most relevant user.
M.13: The symbiote must be able to operate at least at 10Hz	Ensures smooth and responsive perception and control.
M.14: The symbiote must show predictable behavior	Predictability improves user trust and safety during interactions. Also aids learning of the behavioral "grammar".

10.2 Should-Have Requirements

The should-have requirements are shown in Table 9. Although less important, significant effort is made to adhere to these requirements.

S.02 through **S.04** are about detection and error correction. The ES report implemented elementary filters and error handling.

S.01, S.05 through **S.09,** and **S.13** are about the ease of building and modification. These are important not only because they are designed for a swarm robot. They also allow for educational value. These requirements help people who would like to continue the project. It is acknowledged that these requirements are not ”very scientific” and are open to interpretation. These requirements for the mechanical design are already discussed in this report, but are further discussed in the ES report.

S.10, S.11, and **S.12** are about the ability of people to detect the correct emotion. The test method, setup, results, and discussion are treated in the testing and validation chapter. The final justification can be seen in the requirements section of the ES report.

Table 9 Should have requirements for the ES report, with the reason for implementation

Requirement	**Reason**
S.01: The robot should be rechargeable using a universal charger	Improves compatibility and user convenience. Especially during the deployment in the Cyber Zoo.
S.02: The symbiote should be able to detect loud noises >70 dB	Allows for the detection of loud sounds, which are needed for interesting interactions. This is because humans attach much value to sound cues.
S.03: The symbiote should not be triggered by everyday conversation, <65 dB	Prevents false positives on loud sounds during typical use, as part of filtering ambient noise.
S.04: The symbiote should perform error handling on false-positive and false-negative detections	Improves reliability and trustworthiness. Also important for M.14
S.05: The symbiote should allow for modifications	Supports extensibility and user customization. Also important for educational purposes.
S.06: The symbiote should allow options for additional sensors	Facilitates upgrades or adaptation to different use cases. Also important for educational purposes.
S.07: The symbiote should use standard communication protocols	Enhances compatibility with other devices and systems. Especially important for swarm applications.
S.08: The symbiote should use basic tools to construct	Mostly discussed in this report, but extends to the electronics design in the ES report.
S.09: The symbiote should use materials with nationwide availability	Ensures ease of procurement and reproducibility.

S.10: The symbiote should show distinguishable emotions	Enables meaningful human-robot interaction.
S.11: The symbiote should show detectable emotions	Enables meaningful human-robot interaction.
S.12: The symbiote should move naturally with no perceived jumps in speed	Improves realism and comfort during interaction. As discussed in the interactions design chapter.
S.13: The symbiote should be less than 500 euros when bought in bulk	Supports affordability and potential for widespread use. Especially important for swarm applications.

10.3 Could-Have Requirements

The could-have requirements are shown in Table 10. The focus is not on these requirements, but they could prove helpful.

C.01 is about the ability to determine the direction of loud sounds. This was not deemed as important as noticing the sound in general. Later, more research could also be done to explore voice recognition and sound commands.

C.02 is about emotion detection. Although it could prove useful, it is not as important as the other detection methods. Most simple animals are not able to read emotions, but are able to interact with humans in a meaningful way.

Lastly, **C.04** is about ROS 2. ROS 2 is a widespread robotics system that could allow the symbiote to be easily integrated into other projects. The software could be converted into ROS 2-compatible software.

Table 10 Could have requirements for the ES report, with the reason for implementation

Requirement	Reason
C.01: The symbiote could be able to detect the direction of sounds	Would improve spatial awareness and interaction responsiveness.
C.02: The symbiote could be able to detect the emotions of people	Would enable deeper emotional interaction with users. However, it is deemed less important than other factors.
C.03: The symbiote could be less than 500 euros in cost	Supports budget-conscious implementation, especially in educational settings.
C.04: The symbiote could be ROS 2 compatible	Would enhance modularity and integration with modern robotic ecosystems.

10.4 A Short Summary

These requirements, structured hierarchically, help to guide the ES report. They create a framework of technical and interactional requirements that form the starting point for a technical report. They also answer the second research question, as will be mentioned in the next chapter.

11 Discussion

This section addresses the primary research questions guiding the development of the symbiote, with a focus on bio-inspired design, swarming applicability, intuitive interaction, and the symbiote's sensory and expressive capacities.

11.1 Research Questions

The research questions guided the design of the symbiote through the dissection of the vision and objective. Now let us answer and address the questions.

11.1.1 What bio-inspired features can be used to create intuitive interactions?

Through exploration of systems in nature, particularly those found in dogs and arthropods, several bio-inspired features were identified as conducive to intuitive interaction. These include visual expressions inspired by **canine facial markers** (e.g., eyes, ears, body posture) and **antennae behavior** from arthropods. The use of synchronized **eye movements**, **eyelids**, and **antennae gestures** proved effective in communicating emotional states without requiring explicit contextual explanations on what states belong to what emotion. The expressiveness of these features relies on patterns that humans have evolved to recognize instinctively, such as slow motions that indicate calmness and sharp gestures to signal alertness. **By adopting these biologically inspired methods, the symbiote enables interactions that can be deduced from context.**

11.1.2 What technical requirements should the symbiote adhere to be implementable for swarming robots?

To be compatible with swarming robots, the symbiote must fulfill several technical constraints. It must maintain a **modular and lightweight structure** to avoid compromising the host robot's mobility. The symbiote's **low power consumption**, use of standard **microcontrollers,** and support for **I2C communication protocols** facilitate both scalability and robustness. Lastly, simple fabrication, low cost, and hardware abstraction are necessary to allow reconfiguration or replication across multiple robots in a swarm. These requirements are given in the previous section, and they should add to the interactive capabilities to enhance emerging behavior.

11.1.3 How should a robot intuitively respond to a human in an interactive setting?

The robot should respond in a way that mirrors the **social signals** of humans and use their expectations of well-known animals. This is done through **movement, posture, and facial cues**, rather than complex communication. In this project, this was achieved via **eye movement**, **antennae gestures**, and **adjustable eyelids**, all designed to reflect emotional states such as alertness, relaxation, or stress. Intuitive response was further reinforced through **real-time interaction**. The robot adjusted its features dynamically in response to proximity and sounds. These design choices support the robot's ability to engage in **intuitive interactions**, similar to how humans read pets or other humans, thereby fostering a sense of mutual understanding.

11.1.4 What sensing capabilities does the symbiote require to sense human emotions?

Sensing emotional states in humans requires interpreting indirect cues. The symbiote uses **vision and hearing** to detect human presence and emotions. Combining all the sensed data gives information on the position, number, and pose of people, which is often sufficient for estimating intent and mood. These sensing capabilities are inspired by animals' sensitivity to human gestures and presence and allow the symbiote to operate in emotionally aware ways, even without direct emotion recognition.

11.1.5 What should the symbiote do to express its emotions to a human?

Expression of emotion is achieved through a combination of **bio-inspired visual, spatial, and temporal cues**. Drawing on animal behaviors, the symbiote employs **eye movement**, **eyelid position**, **antennae orientation**, and **motion dynamics** to express internal states. Emotional valence is conveyed through **rhythmic or erratic movement patterns**, **pupil direction**, and **blinking frequency**, mimicking how animals use body language to signal fear, curiosity, or excitement. These expressions are designed to be **interpretable by humans at a glance**, relying on biological familiarity rather than cognitive effort. Such expressive capability is essential not only for intuitive interaction but also for enabling emotional reciprocity between humans and robots.

11.2 Vision and Objective

The guiding vision for this project was: ***"Designing a bio-inspired symbiote that aids swarming robots in sensing the environment and expressing themselves to humans in an intuitive way."*** This vision came from the intersection of three research domains: bio-inspired design, swarm robotics, and human-robot interaction. It aimed to create a symbiotic module that not only contributes to the swarm's environmental awareness but also enhances its ability to communicate emotional or behavioral states to humans in a natural, intuitive manner.

The project successfully achieved the central aspects of this vision. **The symbiote design was heavily inspired by biological principles, drawing on behavioral and physical features of animals such as dogs and arthropods**. These references were translated into physical appendages like eyes, eyelids, and antennae, which mimic recognizable emotional cues. By using eye following and antennae gestures, the symbiote facilitates a form of communication that users learn from context. These interactions were found during the explorative phase and confirmed during the tests, where participants were able to associate movements with emotional states when provided with some contextual situations.

From a technical standpoint, the symbiote was designed with modularity and simplicity in mind. **Its construction ensures compatibility with existing swarming robots, such as Traici and Mirte, without significantly affecting their mobility or autonomy.** The system employs components and communication protocols that support scalability. This is an essential feature for swarm implementation. The sensing capabilities, while basic, provided a starting point for contextual awareness. Features like camera sensing and sound detection allowed the robot to perceive human presence and interaction intent, enabling it to respond accordingly.

Several aspects of the project worked exceptionally well. The ideation and prototyping process effectively bridged biological inspiration with engineering implementation, translating animal behaviors into expressive robotic elements. Collaboration with domain experts, including a dog behavior specialist and researchers from the HRI group, enriched the emotional design and confirmed the relevance of the chosen features. Moreover, the project addressed a notable knowledge gap in the field of Human-Swarm Interaction by investigating how individual expressive elements could function within a larger swarm.

However, there are areas where the project can be improved. While the current sensing capabilities provide basic awareness, more advanced emotional sensing, such as facial expression analysis and vocal tone detection signal monitoring, would significantly enhance the robot's capacity to interpret human affect. Additionally, **the user testing phase, though insightful, was limited in scope**. A broader study involving more diverse participants would provide a more reliable validation of the system's intuitiveness and emotional legibility. Another area that remains only partially explored is the symbiote's integration within a functioning robot swarm. Although the design supports swarm deployment, time constraints prevented testing in dynamic, multi-agent swarm scenarios. Embedding the symbiote into actual swarm operations would offer valuable insights into its scalability and behavior in decentralized systems.

Furthermore, the current iteration of the system relied on manually controlled behaviors for demonstration. Future versions should aim to test the implemented autonomous behavior transitions, where sensor input triggers responsive emotional states and movements without human intervention. This would strengthen the symbiote's role as an independently functioning, emotionally expressive entity within a robotic swarm.

In short, the project fulfilled its design vision by creating a functioning, bio-inspired symbiote capable of sensing environmental context and expressing internal states in a way that supports intuitive human understanding. The outcomes serve as a strong foundation for further development and deployment in swarm robotics contexts. While some technical and empirical components require expansion, the project has laid the groundwork for a new form of emotionally aware, communicative swarm agents that bridge the gap between autonomous systems and human observers.

12 Conclusion

This project set out to explore the intersection of bio-inspired design, swarm robotics, and human-robot interaction by developing a robotic symbiote capable of enhancing the intuitiveness of interactions between humans and small swarming robots. Through an iterative design process grounded in research, experimentation, and rapid prototyping, a novel module was created that attaches to terrestrial swarm robots like Traici and enhances their ability to sense and express emotion in a way that is both readable and relatable to human users.

By drawing inspiration from both arthropods and domesticated animals, specifically the woodlouse and the dog, the design embraced both functional and affective communication. The integration of features such as eyes, antennae, and eyelids allowed for a vocabulary of expression, which was refined through expert interviews, behavioral studies, and interactive testing. The iterative process highlighted the importance of creating a "robotic grammar," enabling users to interpret robotic states through context cues.

This work contributes to the emerging field of Human-Swarm Interaction (HSI) by providing a tangible, tested prototype that bridges the emotional gap between humans and machines. The findings show that intuitive interaction does not solely depend on advanced artificial intelligence, but can be effectively achieved through thoughtful physical design rooted in natural analogs. The module developed in this project offers a scalable and adaptable platform for future swarm robotics applications in public engagement, education, and research.

Ultimately, the project demonstrates how integrating sensory and expressive components into swarm robots can foster empathy, improve communication, and open new doors for meaningful human-robot relationships.

13 Future Work

While the current implementation demonstrates the feasibility of an intuitive, bio-inspired swarming robot, several promising directions for future development could enhance both technical performance and interactive richness.

Sensors: Adding touch sensors to the antennae would expand the robot's ability to respond to physical interactions. Touch sensing could enable more nuanced human-robot interactions, especially in crowded or dynamic environments. It would also allow the antennae to be multifunction, contributing to the robot's overall environmental perception (e.g. for navigation and obstacle avoidance), which would be desirable even outside the HRI context.

Interpretation: Several improvements could be made to the sensory interpretation pipeline. Fine-tuning the existing parameters for detection thresholds and filtering could increase reliability and responsiveness. Implementing stereo sound directionality would allow the robot to localize human presence more accurately, especially when paired with voice-based inputs such as pitch, tone, or even voice recognition. Additionally, pose detection would enable a better understanding of human intent and body language. Emotion detection could also be revisited with a more powerful onboard processor, enabling richer affective interactions. Finally, incorporating parity bits and data validation would strengthen the reliability of the communication and processing pipeline.

Actuation: Future iterations could benefit from quieter, more efficient motors to reduce noise pollution during interaction. New expressive features, such as a moving mouth or brows, could significantly broaden the range of emotional states that can be conveyed.

Software and Embedded Systems: On the software side, expanding functionality and adding modular control options would improve scalability and maintainability. Introducing structured safety checks, better data handling, and advanced filtering methods would enhance both system robustness and longevity. Features such as stereo sound interpretation, voice recognition, and tactile input integration could also be further explored in this context.

Mechanical Engineering: Mechanically, the robot could be improved by reinforcing structural components and using back-drivable motors for smoother and more compliant movement. Implementing autonomous charging and refining control systems for locomotion would allow for extended and more independent operation.

Industrial Design: For an industrial designer, the focus on expressive behavior and emotional communication could be interesting. Furthermore, the production process and mechanical design can be improved with a focus on manufacturability and visual appeal.

14 References

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Appendix

A. Project Brief

Personal Project Brief – IDE Master Graduation Project

Name student: Aart Rozendaal   Student number: 4,870,255

PROJECT TITLE, INTRODUCTION, PROBLEM DEFINITION and ASSIGNMENT
Complete all fields, keep information clear, specific and concise

Project title Design of a small swarming robot showing intuitive human interaction

Please state the title of your graduation project (above). Keep the title compact and simple. Do not use abbreviations. The remainder of this document allows you to define and clarify your graduation project.

Introduction

Describe the context of your project here; What is the domain in which your project takes place? Who are the main stakeholders and what interests are at stake? Describe the opportunities (and limitations) in this domain to better serve the stakeholder interests. (max 250 words)

The project takes place at the intersection of robotics, AI, bio-Inspired sensors, and human-robot interaction, a rapidly evolving domain that is redefining daily life. The stakeholders in this domain include researchers, technologists, and companies developing robotics, and most importantly end users - people who would benefit from robots performing everyday tasks. As robots become more integrated into society, they have the potential to assist with jobs that are dangerous, repetitive, or undesirable for humans, improving efficiency, safety, and quality of life (like autonomous vehicles reducing accidents with 92% (LuigiDiLillo,2024)). Quickly becoming irreplaceable like smartphones have in the past (Gartner,2023).

Current limitations in the field stem from the challenge of developing robots that can seamlessly interact with humans and their environments in an intuitive, non-intrusive way. The uncanny valley (Figure 1), where robots that almost resemble humans create discomfort, remains a hurdle in emotional robotics (pollick,2009). Another challenge is enabling robots to function autonomously in real-world conditions while communicating effectively with both humans and other robots.

Robotics can be improved by embracing swarm intelligence, where simple, autonomous robots work collectively to solve complex tasks, similar to how bees and ants function. Coupled with bio-inspired sensors, these robots can become more adaptable and responsive to their surroundings. Together, with improved communication and memory over humans and animals, these robots can help with essential tasks and improve quality of life.

More specifically, Sience Centre TU Delft wants to explore the possibility of small swarming robots to interact with people on campus.

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introduction (continued): space for images

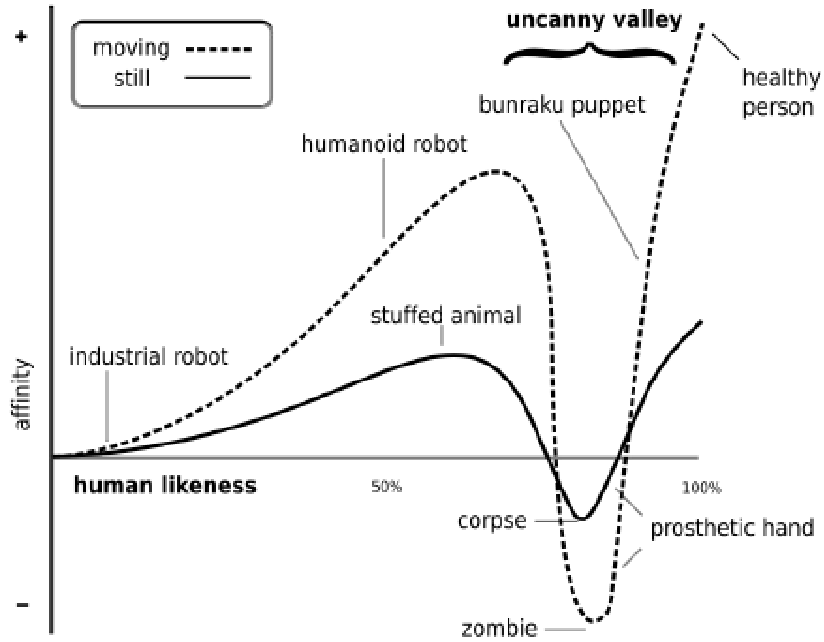


image / figure 1 Shows the uncanny valley and how human resemblance can effect affinity (Wikipedia, 2024)

image / figure 2

Personal Project Brief – IDE Master Graduation Project

Problem Definition

What problem do you want to solve in the context described in the introduction, and within the available time frame of 100 working days? (= Master Graduation Project of 30 EC). What opportunities do you see to create added value for the described stakeholders? Substantiate your choice.
(max 200 words)

In the next 150 days, the problem to solve is the creation of autonomous, self-sufficient robots capable of performing simple, practical tasks in daily human life while interacting naturally with humans, animals, and the environment. The robots must also be able to demonstrate swarm intelligence, showing that a group can handle more complex tasks than one robot alone. Opportunities include using bio-based sensors to enhance their adaptability and environmental awareness. These robots will address the growing need for automation in routine tasks, making them indispensable in areas like outdoor maintenance, public safety and connectivity.

By demonstrating natural interaction, charging autonomy, and communication abilities, these robots can seamlessly integrate into human lives, adding significant value to both individuals and society.

essentially creating a species of robots that becomes indispensable to modern life whilst being self-sufficient able to perform daily tasks, live outdoors, and collaborate with both humans and other robots.

Assignment

This is the most important part of the project brief because it will give a clear direction of what you are heading for. Formulate an assignment to yourself regarding what you expect to deliver as result at the end of your project. (1 sentence) As you graduate as an industrial design engineer, your assignment will start with a verb (Design/Investigate/Validate/Create), and you may use the green text format:

Design and prototype a small autonomous swarming robot using bio-inspired sensors to improve robot and human interaction for performing daily tasks at the Science center at TU Delft.

Then explain your project approach to carrying out your graduation project and what research and design methods you plan to use to generate your design solution (max 150 words)

The project will be split into Research, Ideation and Design, Prototyping and Testing where I try to answer different questions.

Research: What are (future) problems the robots could solve? What implementations of swarming are available? What innovative biobased sensor exist and are relevant. What simple robot designs could suite the problem they try to solve? What environmental factors are presents at the location (e.g. with animals, people and surrounding)? What legislation is relevant?

Ideation & Design: What should the robot look like, be able to do and require? What swarming and interaction behaviors are relevant?

Prototyping: creating a simple prototype or professional version (if I have a team)

Testing: Does the robot fullfill the requirements: Swarming, interactions and autonomy?

Project planning and key moments

*To make visible how you plan to spend your time, you must make a planning for the full project. You are advised to use a Gantt chart format to show the different phases of your project, deliverables you have in mind, meetings and in-between deadlines. Keep in mind that all activities should fit within the given run time of 100 working days. Your planning should include a **kick-off meeting, mid-term evaluation meeting, green light meeting and graduation ceremony**. Please indicate periods of part-time activities and/or periods of not spending time on your graduation project, if any (for instance because of holidays or parallel course activities).*

Make sure to attach the full plan to this project brief.
The four key moment dates must be filled in below

Kick off meeting	30 sept 2024
Mid-term evaluation	24 jan 2025
Green light meeting	16 mei 2025
Graduation ceremony	27 juni 2025

In exceptional cases (part of) the Graduation Project may need to be scheduled part-time. Indicate here if such applies to your project

Part of project scheduled part-time	✓
For how many project weeks	38
Number of project days per week	4,0

Comments:
The project is 45 ECTs (150 days) but will take a full year because of the extra work that will come with the double graduation, as discussed with chair and supervisor.

Motivation and personal ambitions

Explain why you wish to start this project, what competencies you want to prove or develop (e.g. competencies acquired in your MSc programme, electives, extra-curricular activities or other).

Optionally, describe whether you have some personal learning ambitions which you explicitly want to address in this project, on top of the learning objectives of the Graduation Project itself. You might think of e.g. acquiring in depth knowledge on a specific subject, broadening your competencies or experimenting with a specific tool or methodology. Personal learning ambitions are limited to a maximum number of five.
(200 words max)

I think the project perfectly fits both my master programs, personal ambitions and interests.

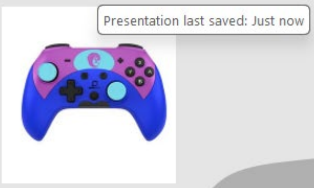
In embedded systems my main interest lays towards working with hardware that is leaning towards robotics. Combining simple software to effectively utilize hardware is what really makes me enthusiastic. This is also why I spent three years at the Lunar Zebro student team working on small moon rovers. Pushing technology and challenging myself by finding solutions for problems in new or extreme situations.

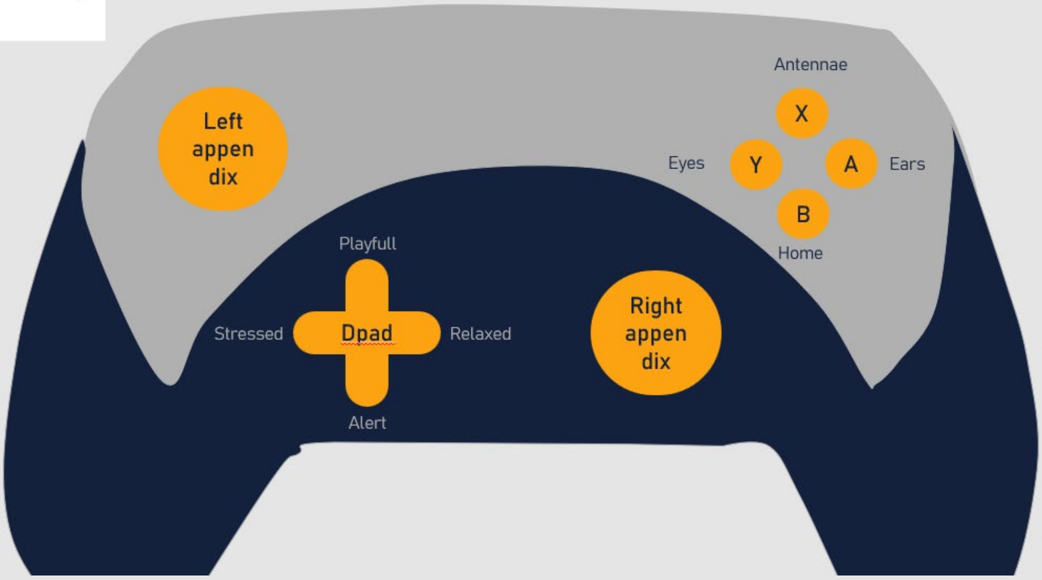
For Integrated Product Design my interest was with the interaction of people with the products they use. Especially looking at what people want and why, sometimes solving problems in ways they could not have foreseen themselves. In my second year of IPD I worked for the police creating a product that was used by the dog handlers and the dogs themselves creating a very interesting ideation, prototyping and testing dynamic. This also grew my interest in design for and based on animals.

Combining these two interests with my interest in nature and bio based sensors makes this project a good fit for my graduation project. I hope to learn more about, bio based sensors, human and robot interaction and swarming.

B. Controller layout

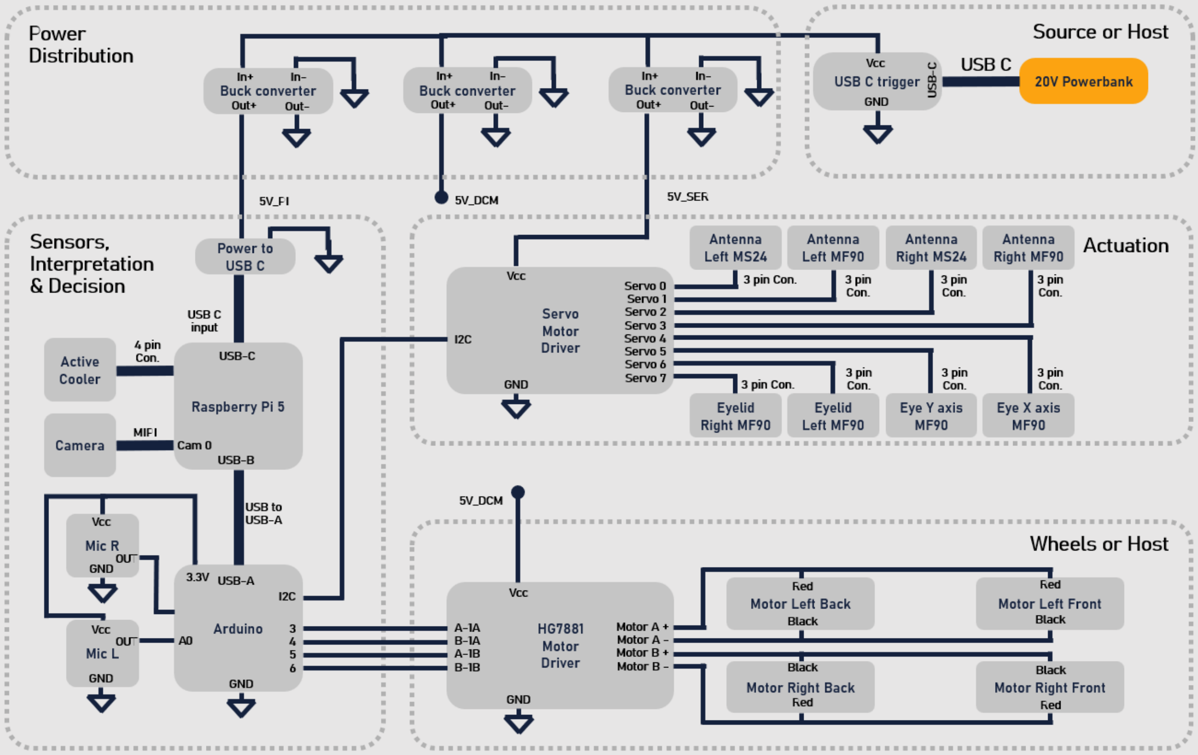
Below the figure shows the controller layout





C. Schematics

Below the figure shows the electrical shematic



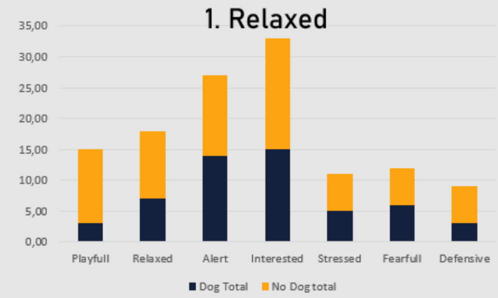
D. Answer sheet for the explorative test

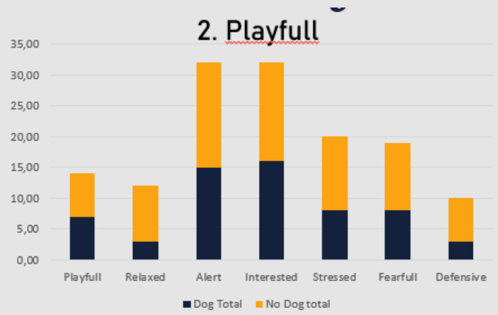
Configuration 1:

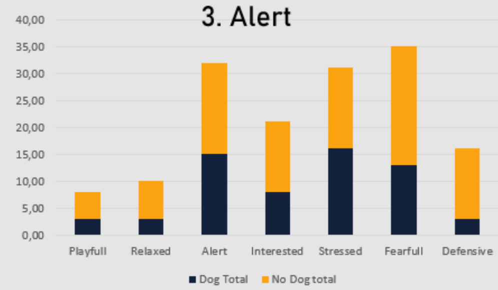
	1	2	3	4	5	6	7
Playful	O	O	O	O	O	O	O
Relaxed	O	O	O	O	O	O	O
Alert/Interested	O	O	O	O	O	O	O
Stressed	O	O	O	O	O	O	O
Fearful	O	O	O	O	O	O	O
Defensive	O	O	O	O	O	O	O

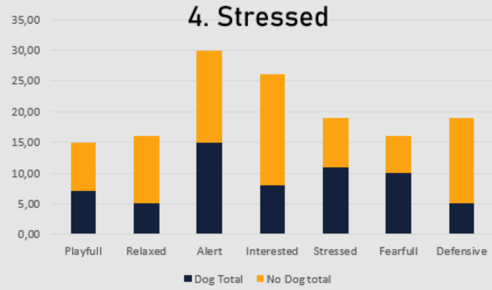
E. Results explorative test

Ears and Eyes

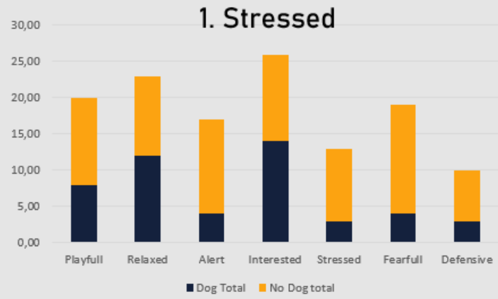


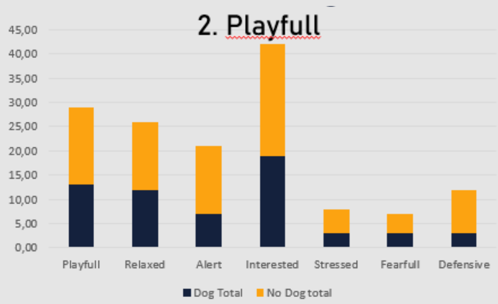


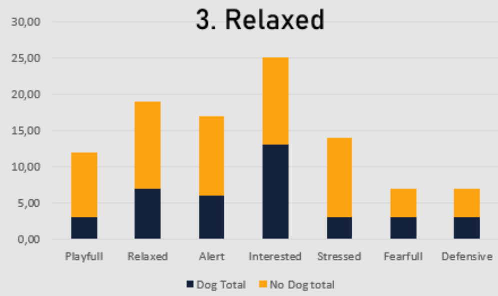


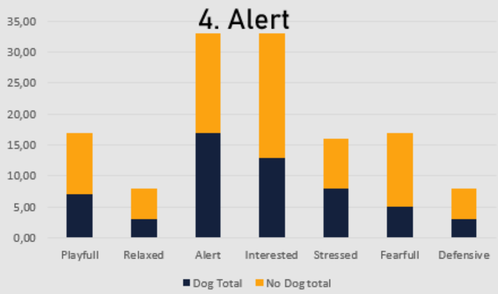


Antennae and Eyes

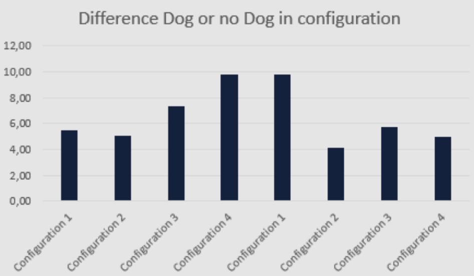


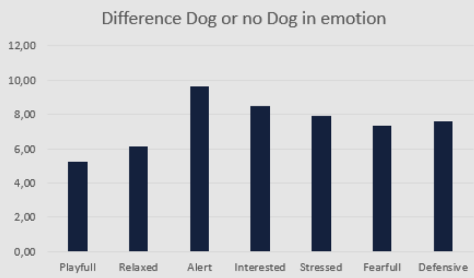






Differences between dog owners and non-dog owners





F. GitHub link

https://github.com/aartrozendaal/flip

G. Bill of Materials

Below is the Bill of Materials. The up-to-date version can be found on: https://github.com/aartrozendaal/flip

One Time Purchases					
Part Nr	**Name**	**Order Quantity**	**Total price (Euros)**	**Retailer**	**Link**
T.00.01	PopTop Minibird Draadloze Controller	1	€ 34.99	Bol	
T.00.02	USB-C charger	1	€ -		
T.00.03	Micro-HDMI naar HDMI Female kabel - Zwart - 200r	1	€ 5.34	KiwiElectronics	
T.00.04	Raspberry Pi 27W USB-C Power Supply - Wit - EU	1	€ 13.90	KiwiElectronics	
T.00.05	mouse	1	€ -		
T.00.06	keyboard	1	€ -		
T.00.07	screen	1	€ -		
T.00.08	HDMI kabel	1	€ -		
T.00.09	screwdriver set	1	€ -		
T.00.10	Solder Iron	1	€ -		
T.00.11	Soldering tin & Wick	1	€ -		

Per Robot Purchases					
Part Nr	**Name**	**Order Quantity**	**Total price (Euros)**	**Retailer**	**Link**
E.00.01	Arduino Wifi Rev 2.0	1	€ 54.95	KiwiElectronics	https://www
E.00.02	Miuzei Servo Motor MF90	1	€ 26.99	Amazon	https://www
E.00.03	Miuzei Servo Motor MS24 20Kg	1	€ 25.99	Amazon	https://www
E.00.04	Nidec DC motor MG16B-060-AA-00	1	€ 180.44	Digikey	https://www
E.00.05	Raspberry Pi 5 - 16GB	1	€ 135.51	KiwiElectronics	https://www
E.00.06	Raspberry Pi Active Cooler	1	€ 5.92	KiwiElectronics	https://www
E.00.07	32GB microSD	1	€ 11.48	KiwiElectronics	https://www
E.00.08	Raspberry Pi Camera 3 Wide	1	€ 40.52	KiwiElectronics	https://www
E.00.09	Raspberry Pi Camera Kabel	1	€ 1.20	KiwiElectronics	https://www
E.00.10	Microphone MAX4466 Adafruit	2	€ 16.44	KiwiElectronics	https://www
E.00.11	Dc-Dc 12V / 24V Naar 5V 5A Buck Converter	3	€ 29.73	Amazon	https://www
E.00.12	INIU Power Bank, 100 W 25000mAh Powerbank	1	€ 59.99	Amazon	https://www
E.00.13	USB C trigger board	1	€ 10.49	Amazon	https://www
E.00.14	Motordriver HG7881	1	€ 8.99	Amazon	https://www
E.00.15	adafruit motorshield v2	1	€ 22.98	KiwiElectronics	https://www
C.00.01	USB-A to USB-B Cable - 0.5 meter	1	€ 2.50	KiwiElectronics	https://www
C.00.02	jumper wires	1	€ 4.22	KiwiElectronics	https://www
X.00.01	Inserts M2	1	€ 10.00	3D-jack	https://ww
X.00.02	Inserts M3	1	€ 10.00	3D-jack	https://ww
X.00.03	M2 screws	1	€ 5.74	3D-jack	https://ww
X.00.04	M3 screws	1	€ 6.64	3D-jack	https://ww
X.00.05	cable organizers	1	€ 9.95	Bol	https://ww
X.00.06	Bearings	4	€ 9.48	RS	https://nl.r
P.00.01	PLA-Metallic	2	€ 56.92	BambuLab	https://eu.s
P.00.02	PLA-White	1	€ 23.38	BambuLab	https://eu.s
P.00.03	PLA-Color	1	€ 23.38	BambuLab	https://eu.s
P.00.04	TPU-Grey	1	€ 40.67	BambuLab	https://eu.s

Category	Bulk Price/ Robot (Euros)	Price/ Robot (Euros)	Order Price (Euro)
Tools	€ -	€ 54.23	€ 54.23
Electronics	€ 606.64	€ 631.62	€ 631.62
Cables	€ 4.08	€ 6.72	€ 6.72
Extras	€ 24.38	€ 42.33	€ 42.33
Printing	€ 23.05	€ 144.35	€ 144.35
Total without extra costs			
Category Sum	€ 658.15	€ 879.25	€ 879.25
Delivery	€ -	€ 67.97	€ 67.97
Extra costs	€ -	€ 20.00	€ 20.00
Total			
Total	€ 658.15	€ 967.22	€ 967.22

H. Informed Consent From

Below is the informed consent form

Delft University of Technology
HUMAN RESEARCH ETHICS
INFORMED CONSENT FORM

Aart Rozendaal
Design of a Small Swarming Robot
Showing Intuitive Human Interaction

Introductory text

You are being invited to participate in a research study titled: Design of a Small Swarming Robot Showing Intuitive Human Interaction. This study is being done by Aart Rozendaal from the TU Delft.

The purpose of this research study is to investigate the human perception of emotions in robots and will take you approximately *5-10* minutes to complete. The data will be used for improving the design of the robot made during the Master Thesis project of Aart Rozendaal. We will be asking you to look at several configurations of the robot and tell what emotion you are interpreting.

As with any online activity, the risk of a breach is always possible. To the best of our ability, your answers in this study will remain confidential. We will minimize any risks by anonymising your answers and storing them in a safe location.

Your participation in this study is entirely voluntary and you can withdraw at any time. You are free to omit any questions. Because the data is made anonymous answers can only be altered during the experiment.

PLEASE TICK THE APPROPRIATE BOXES	Yes	No
A: GENERAL AGREEMENT – RESEARCH GOALS, PARTICPANT TASKS AND VOLUNTARY PARTICIPATION		
1. I have read and understood the study information dated 11-04-2025 or it has been read to me. I have been able to ask questions about the study and my questions have been answered to my satisfaction.	☐	☐
2. I consent voluntarily to be a participant in this study and understand that I can refuse to answer questions and I can withdraw from the study at any time, without having to give a reason.	☐	☐
3. I understand that taking part in the study involves: • Watching a short video • Answering questions about emotional perception. • Photos will be taken and anonymised	☐	☐
B: POTENTIAL RISKS OF PARTICIPATING (INCLUDING DATA PROTECTION)		
6. I understand that taking part in the study involves the following risks: Working with a non-CE-certified product. I understand that these will be mitigated by: Internal TU Delft Device certification.	☐	☐
7. I understand that taking part in the study also involves collecting specific personally identifiable information (PII): Photos that will be anonymised.	☐	☐
9. I understand that the following steps will be taken to minimise the threat of a data breach and protect my identity in the event of such a breach. Data is stored separately from the PPI	☐	☐
10. I understand that personal information collected about me that can identify me, such my name, will not be shared beyond the study team.	☐	☐
11. I understand that the (identifiable) personal data I provide will be destroyed after 2 months of completing the project unless anonymised and used in the report.	☐	☐
C: RESEARCH PUBLICATION, DISSEMINATION AND APPLICATION		
12. I understand that after the research study the de-identified information I provide will be used for The Master thesis of Aart Rozendaal	☐	☐
13. I agree that my responses, views or other input can be quoted anonymously in research outputs	☐	☐
D: (LONGTERM) DATA STORAGE, ACCESS AND REUSE		
16. I give permission for the de-identified data on emotional perception of robots that I provide to be archived in TU Delft repository so it can be used for future research and learning.	☐	☐
17. I understand that access to this repository is open	☐	☐

Signatures

Name of participant [printed] Signature Date

[Add legal representative, and/or amend text for assent where participants cannot give consent as applicable]

I, as legal representative, have witnessed the accurate reading of the consent form with the potential participant and the individual has had the opportunity to ask questions. I confirm that the individual has given consent freely.

Name of witness [printed] Signature Date

I, as researcher, have accurately read out the information sheet to the potential participant and, to the best of my ability, ensured that the participant understands to what they are freely consenting.

Researcher name [printed] Signature Date

Study contact details for further information: [*Name, phone number, email address*]