Development of an Emotionally Expressive Robot Platform

MF2059 KTH Mechatronics Advanced Course

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Abstract

This project was set to focus on developing a social robot for child interaction.The goal was to create a tabletop robot that, through nonverbal communication, was able to express the six basic emotions of anger, disgust, fear, happiness, sadness and surprise. It should do so whilst providing a safe, transparent, explainable and accountable interaction, complying with *UNICEFs policy guidelines on AI for children. Haru*, the social robot project led by Honda Research Institute of Japan, was used as the main source inspiration.

To start of the project, a state of the art analysis was performed, where several fields of study and existing social robots were investigated. From here, three concepts were derived: *Improved Haru*, the *Egg*, and the *Snowman*. Trough evaluation, the *Egg* was deemed the best candidate for further development. After an iterative second design process, a final solution was reached. The report examines the final mechanical and electrical design as well as the software in use in more detail. The dimensions of the robot are 28 cm in height (in its closed state) and 20 cm in base diameter. The total cost of the robot is 918 €.

Validation through questionnaires, a reliability test as well as a noise test were performed. The results indicate that colours and graphics help the user to perceive the emotions more accurately. Angry, sad and shy were the emotions with the highest correct-perception-rate whilst happy, surprised and disgust had the lowest. The robot's reliability showed great potential as no component reached temperatures worthy of concern. However, one of the motors got a recurring failure. The maximum equivalent noise level was 46 dBA, measured at 1 meter away from the robot. It was deemed that the robot met most of the stipulated requirements. Some of the future work suggested are improved mechanics, design and motion control, minor changes in electronics, the implementation of FSM as well as the expansion of explainability and user interaction.

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Glossary

AI Artificial Intelligence. 1, 2

AUs action units. 7

CAD Computer Aided Design. 26, 61

DoF Degrees of Freedom. 22, 28, 29

FACS Facial Action Coding System. 7

FDM Fused Filament Fabrication. 29

FSM A finite-state machine. 43

HRI Human-Robot Interaction. 6, 12, 13

HRI-JP Honda Research Institute Japan. 1, 2

LED Light Emitting Diode. 34, 36, 40–42

OGIP Office of Global Insight and Policy. 1

OpenCV Open Source Computer Vision Library. 42, 57

pHRI physical Human–Robot Interaction. 13

SOTA State of the art. 4, 34

TTL Transistor-Transistor Logic. 36

UNICEF United Nations Children's Fund. 1, 2, 11, 18

USB Universal Serial Bus. 36, 38, 39

Chapter 1

Introduction

The idea of interacting with automated machines goes back to the ancient times [1]. However, it took many years of technological development before being able to talk about fully automated machines and Artificial Intelligence (AI) [1],[2].

Nowadays, AI enables the design of intelligent machines and robots with interfaces, which provide two-way interaction with humans. This, in turn, has led to the study of the social capability of a robot. Social robots have no punctual definition but a common characteristic, except the interactivity, is that they have the ability to express thoughts and emotions [3]. Such types of robots have become increasingly popular in recent years, a trend that grew significantly during the Covid-19 pandemic [4].

1.1 Background

Social robots have proven to be usable in several different areas. They are able to handle tasks in society such as receptionists, safeguards [5] and within healthcare. The integrated AI technology contributes to easier decision and diagnoses making [6] but also to the promotion of mental health [7]. In addition, studies have shown a beneficial contribution in the field of education. Studies have been done on the possibility of using these robots as an aid for children with autism [8], or as a complement for teachers in school [9]. These studies originated in an initiative from United Nations Children's Fund (UNICEF) that aimed to understand how AI can protect, provide for, and empower children [10].

This project has been inspired and is based on a previous study of a social robot developed by the Honda Research Institute Japan (HRI-JP), named Haru. An example of Haru expressing emotions can be seen in figure 1.1 According to the Office of Global Insight and Policy (OGIP) "Haru is a prototype robot that aims to stimulate children's cognitive development, creativity, problem-solving and collaborative skills" [11]. Haru has been developed in accordance with UNICEF's guidelines and aims to meet at least two of them; namely to "Prioritize fairness and non-discrimination for children" and "Provide transparency, explainability, and accountability for children" [10]. In collaboration with UNICEF and universities from around the world, including KTH Royal Institute of Technology, Honda Research Institute Japan is now looking for potential improvements in the Haru robot and new designs. This project aims to develop a new robot.

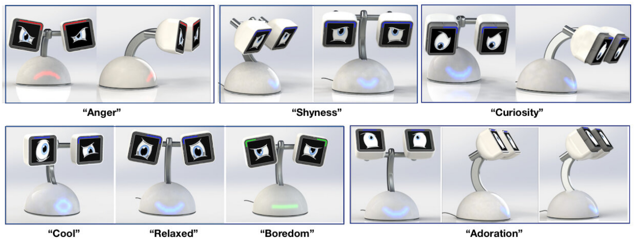


Figure 1.1. *The Haru robot expressing emotions [12].*

1.2 Scope

The scope of this "open ended" project is to develop a platform for a social and emotionally expressive robot. The robot will be developed in accordance with UNICEF's global insight policy on AI for children, and requirements defined by the team that were accepted by the project stakeholder.

This takes the form of a project that extends over two semesters and two different courses. During the spring semester (phase one of the project), a prestudy and research is carried out on relevant articles, existing solutions and the ethical aspects of this project. The team's task is to develop a concept on a social robot and define requirements in order to enable the design process of a potential prototype. During the autumn semester (phase two), a physical prototype should be constructed. The students are then asked to collaborate and use their knowledge within the field of mechatronics.

Overall, developing a social robot can take many year. Given the time limitation of this project it was necessary to define an area of focus. Expressing emotions is a crucial part to social interaction. Therefore it was decided to focus on the emotionally expressiveness of the robot.

1.3 Requirements

This project was initialized with very general requirements, which means that the group had to set its own requirements. A list, including all the defined requirements which were presented and confirmed by the stakeholder, can be seen below. The requirements were divided into two categories. First, minimum requirements expected to be delivered by the project group and achieved by the prototype. Secondly, nice-to-have requirements that are not as strict but would be appreciated by the stakeholder if they were implemented.

Must-have-requirements

1. The robot should comply with requirements 3 and 6 from UNICEFs policy guidelines on AI for children.
   a) Prioritize fairness and non-discrimination for children.
   b) Provide transparency, explainability, and accountability for children.
2. The robot should be understandable by people of all ages, but specifically designed for children between the ages of 5 to 16.
3. The robot should be able to express emotions through body movement and/or facial features.
4. The robot should be able to express the 6 basic emotions of: happiness, sadness, anger, fear, surprise, and disgust.
5. The robot should provide safe interaction with its user, this in terms of both physical and psychological safety.
6. The robot should be reliable and be able to run for several hours without issues requiring service.
7. The robot should have multiple Degrees-of-Freedom. Motors and sensors should enable required localization and perception.
8. In addition to the hardware design Motion control, planning algorithms and software for enabling reliable and safe operation should be developed.

Nice-to-have-requirements

1. The robot should be able to track a person in its surroundings.
2. The robot should be able to greet the user upon first interaction.
3. The robot should be able to express itself using additional nonverbal channels such as sound, colour, haptics and/or graphics.
4. The robot should not produce noise levels above 45dB from a distance of one meter.
5. The dimension of the robot should be in the interval: height: 10-40 cm, base: 5-30 cm

1.4 Readers Guide

Including the introduction this report consists of nine chapters. It starts with a **State of the art (SOTA)** review where previous research and solutions are reported, which are relevant for our work. It is followed by a **concept design** chapter where we developed our own concepts based on the knowledge gained from the SOTA. Given the concept designs the **methodology** chapter introduces the second phase of the project. First, a final concept is chosen and afterwards the approaches to implementation as well validation and verification are presented. The mechanical design, software and electronics of the prototype are explained in the **implementation** chapter. The implementation is followed by a **validation and verification** of the prototype. The results of the previous are presented in the **result** chapter. The report ends with a **discussion** and a chapter with suggested **future work**.

1.5 Team Structure and Management

To create a more efficient workflow, when applicable, the team was divided into sub-groups with each sub-group focusing on a set of tasks (see figure 1.2). During meetings, these tasks were clearly structured and divided. Each period a new team leader was elected. The team leader had the responsibility to lead the meetings as well as keeping track of where we stood in the project and what needed to be done next. One of the team members, the communication manager, was responsible for the communication between the team, the supervisor, and the stakeholder. This role was also switched between team members over the different study periods.

An overarching time plan, with all the deadlines and milestones, was made at the beginning of each study period. In addition, the planning was refined in two weeks intervals. One fixed meeting was held weekly, with additional meetings held if deemed necessary, with the purpose of sharing the progress of different sub-groups between the team members, discussing issues, upcoming deadlines and assigning new tasks.

Micosoft's application "Teams" was used for uploading and sharing documents and files, while Meta's Messenger was used as an everyday communication channel between the group members. Finally the communication between the group, the group coach and the stakeholder was done via e-mail.

Throughout the project, an inventory has been kept of all components that has been used, see appendix F.1. This to enable an easy handover for future work but so that the group will know what to return to the stakeholder at the end of the project.

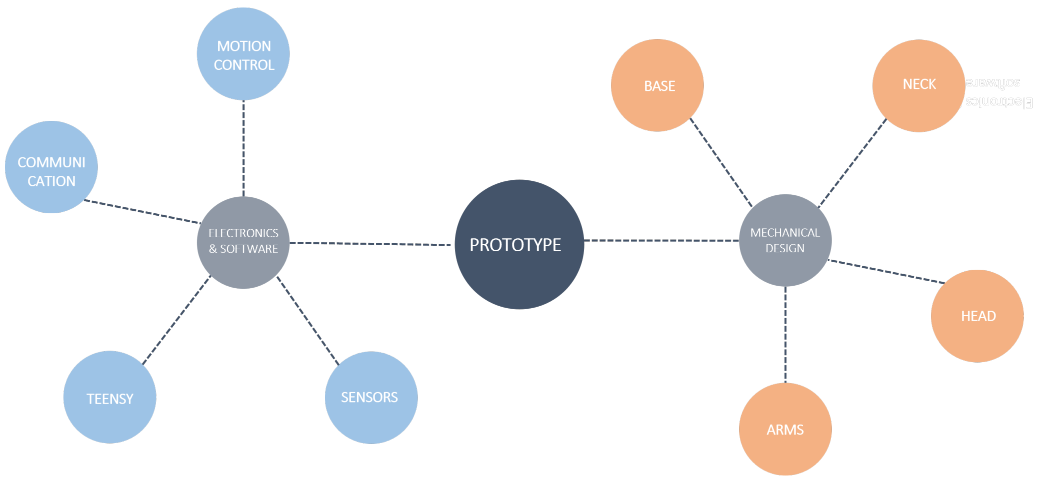


Figure 1.2. *The different subsystems of the electronics and software and mechanical design.*

Chapter 2

State of the Art

This section goes through the results of the research done, summarizing the most important takeaways from existing areas of research, and highlighting ideas, principles and concepts relevant to the continuation of the project. Before going into the different topics researched, here is a quick mention of our research methodology.

The project was quickly determined to be one that would require information from several different fields of research. The following research questions were formulated as the basis for our research.

- Emotional modeling, what emotions are there, and how can they be modeled?
- Expression of emotions. How can a human or other actor successfully express emotions to a human observer?
- Human-Robot Interaction (HRI). How can a robot interact with people in a natural and trusting manner, while not compromising safety?
- Existing products. What similar robots have been created and why are they designed the way they are?

With answers to these questions, the group then had a basis to be able to design the robot.

2.1 Emotional Models and Universality

To implement successful expression of emotions in a robot. A topic as abstract as emotions need to be discretized, or at the very least translated into some form of a tangible model, that can be used to determine the actions of the robot.

Trying to explain and categorize different emotions is a long-studied field, with Darwin's *"The Expression of the Emotions in Man and Animals"* often considered as one of the pioneering studies [13]. Particularly important for this project is the notion of universality, that there exists universal emotions with expressions that are understandable for all humans independent of culture. Since then, there have been many studies and articles debating this topic with results being both supportive [14][15] and critical [16][17][18]. Although the theory of universal emotions is challenged, the six basic emotions proposed by Paul Ekman have been used in many characterization studies and therefore have an abundance of data available. In addition, they are also a well defined set of distinct emotional expressions, lending themselves very well to implementation on a robotic platform. We have therefore chosen to focus on the expression of the six basic emotions throughout this project, the emotions being happiness, sadness, anger, surprise, fear and disgust. This discrete set is sufficient for a proof of concept, but could be further developed to facilitate more complex emotional expression, for example using the circumplex model of emotions [19]. Note however that in interaction with children, the negative emotions should be used very carefully to maintain a psychologically safe interaction. Expressing negative emotions towards a child, outside of a storytelling context, could have negative consequences.

2.2 Expression of Emotions

In this section, studies on how humans best express emotions through different mediums is presented. This is a well researched area and the information found was summarized in a table seen in appendix A. This is to be applied when designing the robot.

2.2.1 Facial Expressions

A facial expression is a shape one's face can take for example a smile. While an emotion is a feeling in your body, like happiness. In other words, different facial expressions can be used to reflect different emotions.

With 43 muscles in the face, humans can create thousands of different expressions. To simplify things, Paul Ekman have divided these to seven universal facial expressions of emotions: happiness, sadness, anger, fear, surprise, contempt and disgust[20]. To describe these emotions, the Facial Action Coding System (FACS) was introduced. Each facial movement is categorized into action units (AUs) and these units can then in combination be mapped to specific facial expressions and emotions[20]. For instance, a cheek raiser (AU=6) + a lip corner puller (AU=12) is interpreted as joy or happiness[21]. For this project we have chosen to focus on the six basic emotions mentioned in section 2.1.

Another facial expression technique is Kismet. The expressions are generated using an interpolation-based technique over a three dimensional space. The three dimensions are stance, valence and arousal, see 2.1. Depending on the amount of each dimension, an emotion can be generated. Kismet is created considering both believability and readability. Believeability refers to how believable or life-like it actually looks and readability refers to how well it can be interpreted. [22]

Facial expressions can be connected to different emotions. Different areas of the face say more or less depending on what emotion is being interpreted. Both the

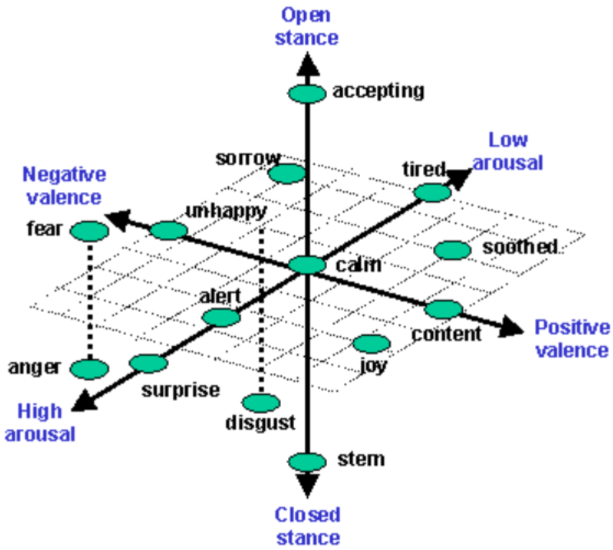


Figure 2.1. *The three dimensional space of the kismet technique.[22].*

eyes, mouth and the brows are features that have a big role in most of the six basic emotions [20].

2.2.2 Body Language

Body language is an important part of nonverbal communication between humans and could therefore be a vital part of the robot design [23]. Compared to facial expressions, body language is a less researched topic but there are still many studies performed.

For the design of the robot we needed to know if there exists any archetypal body language expressions for different emotions. If there is, what movements are the most important for expression and which ones do not matter as much for an observer? Studies performed by Walbott [24], Coulson [25] and De Meijer [26] try to answer this question with differing methodology. In his study, Wallbott had 12 actors perform according to different scenarios corresponding to different types and intensities of emotion. Their movements were filmed and could thereafter be judged according to several factors such as head position relative to body, arm position, hand motion, body weight balance, and several others. From the classification of the labeled video clips, the distinctive posture and motion for each of the studied emotions could be decided. Similar methodology was used by De Meijer in his study where three actors were videotaped and the tapes were reviewed. The focus of this study was however the classification of emotions based on the ”gross body movement”, not the static posture. In his study from 2004, Coulson used a different methodology. Computer generated images of a mannequin were generated, where the pose of the mannequin was varied through it’s seven degrees of freedom. The

176 poses were rendered from three viewpoints each and presented and individually judged by a group of 61 students (age 18-50). For each image, the students were asked to pick which of the six basic emotions best described the pose. The most fitting pose for each emotion was thereafter calculated as the one with the highest concordance between all participants.

The studies mentioned above all give some perspective of the archetypal body language related to each basic emotion. This was used to determine the most important degrees of freedom for expression through body language, and what degrees of freedom that were to be included in the design. A table summarizing this can be found in appendix A.

One important note is that all studies mentioned above researched emotional expression and interpretation of adults, whereas the robot to be designed is meant for younger children, and that the findings of the studies do not necessarily transfer between the two groups. Studies performed by Beck et al. [27] and Ross et al. [28] show that children do in fact react to the same cues as adults, albeit with lower consistency. In the study, Ross and his colleges found that children above the age of 8,5 performed almost at the same level as adults, while younger children were rapidly improving in from lowest studied age group of 4-5 years of age. This implies that the findings regarding adult's body language are applicable to the robots target group of 5-16 year old's, although recognition performance is expected to be lower for the younger children.

2.2.3 Combination of Body Language and Facial Expression

To correctly understand nonverbal cues in others is a very important aspect of social interaction. As stated above both facial expressions and body language are crucial when it comes to displaying emotions. Many studies have been made about how emotions are perceived by facial expressions alone, as well for body language. But in real-life, humans' perceptions of emotions are a combination of both facial expression and body language. One study investigated the relative contributions of the face and the body to the accurate perception of basic emotions [29]. They chose to use dynamic stimuli (video clips) instead of static stimuli (pictures), since the static stimuli don't capture all the necessary dynamic patterns which then may influence the emotion recognition. In addition to that, extensive dynamic facial, and body movement, like rotating, vertical movement, or tilting, may also serve as an important aspect of perceiving emotions [30].

These dynamic stimuli were made with actors portraying the six basic emotions. In the study they conducted 2 experiments, experiment 1 and experiment 2. In the later, they showed sixty participants in the age between 18-28, 3 dynamic stimuli, face, body and one with both face and body see figure 2.2. The participants were then asked to identify which of the 6 basic emotions that was displayed. The conclusion that could be drawn from the results, were that clips with face and body alone would provide enough information to identify the right emotion. But the participants were most accurate at identifying the emotion of the face + body

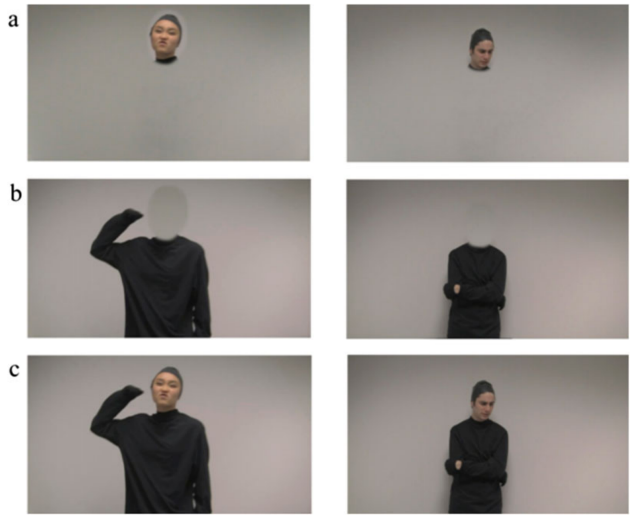


Figure 2.2. *Still frames from video clips displaying anger and sadness, (a) face only, (b) body only and (c) face + body [29].*

video clips and least accurate at the body alone clips, which can be seen in figure 2.3. They also found that isolated facial expressions had minimal confusability between positive and negative emotions, but isolated body on the other hand were misrecognized nearly at the same rate as they were correctly recognized.

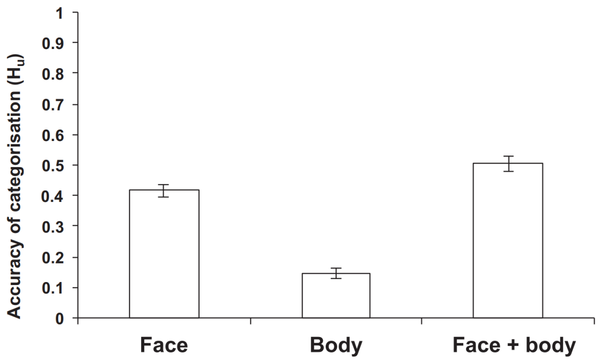


Figure 2.3. *Accuracy of rating the 3 dynamic stimuli [29].*

However, there are also studies that had the opposite findings. A recent work compared the recognition of affective faces and bodies [23]. The participants were asked to rate the affective valence of some static images portraying tennis players. Either the tennis player was winning a critical score, or they were losing one. The static images were presented as: face, body, face and body. The results revealed that participants, when rating the facial expression alone, failed in differentiating the winners from the losers, but when faces were presented with the right context body, the participants easily differentiated the winners from the losers. They noticed that body context basically changed the processing of the face. But during a peak intensity moment, like in the images in the study, the face expression would become non diagnostic for the affective valence of the situation. This may influence the results of the study. As for another study the results were similar to the first study [31]. There they found that participants made much more accurate decisions when the face was accompanied with the right contextualized body, than with a wrong body. From the above findings, the conclusion is that a combinations of both facial expressions and body language may leads to a better recognition of emotions.

2.2.4 Colours

To create sensory enriched environments for children, colours are often used [32]. It is an easy way to stimulate a child's mind and is therefore present in most toys, educational material, décor, and media that children interact with [33]. To play into this stimulation, as well as create familiarity with something children already know, it was thought to incorporate a specific colour for each of the six emotions.

To adhere to the *UNICEFs policy guidelines on AI for children*, the robot should be understandable by all, and that includes the colour-emotion association. An investigation into the cultural differences of this relationship was therefore made. In a study done by Jonauskaite et al., it was found that there are somewhat of a global homogeneity but differences can be found on a national basis (and individual as well) [34]. In the study, 711 participants' answers on the association between 12 colour terms and 20 emotion terms were analysed. Participants were adults from four countries, the UK, Greece, Germany, and China. In terms of cultural differences related to this report, white was associated at a higher frequency with negative emotions in China compared to any other examined nation. The same can be said for yellow in Greece. However, similarities could also be found. In the same study, it was observed that strong colour-emotion associations were present for red, black, and pink regardless of participants' country of origin. Red and pink were associated with love and black with sadness. Red also had a strong emotional connection, but to a lesser extent, to anger. It was also concluded that, although the rest of the colour terms could not be linked to a specific colour term, they were associated with either positive or negative emotions. Positive associations were made for blue, green, orange, purple, turquoise and white. Negative associations were made for brown and grey [34]. However, blue being a happy colour can be contradicted by Löffler et al, who state that the colour is a metaphor for sadness in the saying "feeling blue" and therefore suitable to express the same emotion in a social robot [35].

A study by Boyatzis and Varghese further states that children have a mostly positive reaction to bright colours and a dislike for darker colours, which is in line with Jonauskaite et al. findings [36]. It will therefore be presumed that children and adults have roughly the same colour-emotion association.

By examining the stated research above, a colour was selected for each of the six universal emotions. Out of all the non-verbal ways of expression, besides facial expressions and body language, colour is the most important one. However, using multiple modalities when conveying emotions from a robot to its user are preferred. It will increase the level of understanding further [37].

2.2.5 Vibrations

To further help express emotions, the use of vibrations in robots was examined. Vibrations were generally found to convey negative emotions and vibrations with a high intensity were perceived as an expression of angry emotions. The study by Song and Yamada therefore strongly advised against using vibrations when trying to express positive emotions. The study further observed that using vibrations as the only modality was ineffective and confusing to the user [37].

2.2.6 Sound

The last modality to be investigated was sound. The same study as above stated that rising sounds were found to be strongly connected to angry emotions while falling sounds were strongly associated with sadness. Flat sounds were hard to link to any emotion. It was also found that when the robot used sounds in an attempt to express relaxation, it was hard for the user to categorise the emotion [37].

Furthermore, another study found that the musical parameters of pitch, intonation and timbre are important when expressing intentions and emotions in socially interactive robots. The pitch should range between 100 and 1,500 Hz to simulate the range used in normal human communication. Intonation is used to show different intentions of its producer. For example, a rising intonation is used when people ask something. Lastly, timbre is the quality of sound and a way to convey characteristics, such as age, gender, personality etc., of the robot [38].

2.3 Human-Robot Interaction

When creating a social robot, Human-Robot Interaction (HRI) is an important research topic to take into account. The goal is to create a trusting and safe robot that a user can interact with.

Just as people, it is assumed that it only takes as little as 100ms to form impressions of robots [39]. Because of this, how we perceive a robot is very important. A robot larger than a human, with a highly authoritative, machine-like appearance creates a very different appearance than a small, friendly looking robot. This shows that the form factor of the robot plays a big role in how it will be perceived. Another important aspect when designing a robot is the embodiment of it. Both the trust and engagement rises if it is physically embodied opposed to it only being displayed on a screen [40][41]. This also leads into the aspect of anthropomorphism, which is defined as the tendency to attribute human characteristics to inanimate objects, animals and others with a view to helping us rationalize a situation [42]. In a study to show the role of trust in child-robot interaction made by Zguda et al, they introduced a semi-humanoid robot to Polish kindergarten kids to study their first encounter with it [43]. From this, it was concurred that the level of anthropomorphization incurs some risks, such that human like features also come with expectations that the robot would interact the same way a human would. This was seen as they tried to get its attention by raising their hands and waiving to it. Moreover, they sympathised with the robot as it was only two years old and asked if it had any parents to take care of it. With these risks of the robot not being understood and doing as it was expected the level of anthropomorphization still is a useful tool to help engage interactions. Further research on how children trust robots has been done by Geiskkovitch et al [44]. They conducted an experiment to examine how robot errors affect young children's (3-5 years old) trust in robots. The results suggest that besides the importance of first impressions, a child will side with a robot that has previously proven to be trustworthy. This in terms of it not repeating errors when providing information. In addition to this, Theories like the Uncanny Valley [45] imply that the more human-like robots become, the more natural the interaction; nevertheless, what is natural between humans is not necessarily natural with a robot. This project needs to find a balance so that the robot is both approachable using some human-like features but not too many so that it will become frightening and end up in the uncanny valley, see figure 2.4.

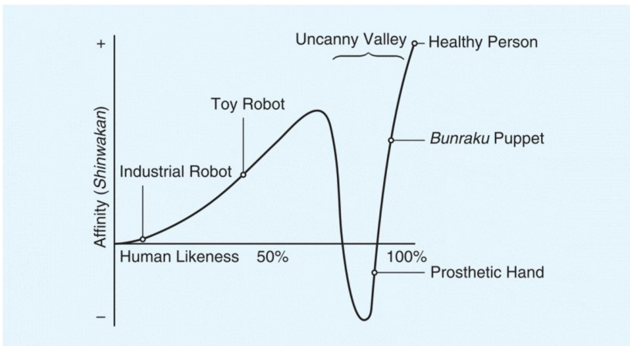


Figure 2.4. *The uncanny valley, the proposed relation between the human likeness of an entity, and the perceiver's affinity for it [45].*

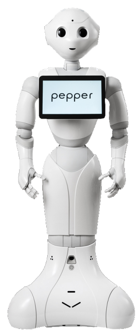
As previously mentioned, the non-verbal communication plays an important role in showing emotional expressions. In this includes also the part of affective touch which has a fundamental role in human development, social bonding, and for providing emotional support in interpersonal relationships. This is something that Andreasson et al. has done a study on and how to express emotions to a small humanoid robot via touch [46]. During the study, participants acted more negatively when they were prohibited from touching the physically embodied robot than when they were allowed to interact with the robot via touch.

A final note on HRI is the safety aspect, both physical and non-physical safety needs to be taken into account. physical Human–Robot Interaction (pHRI) consists of risks of collisions, avoid sharp edges, lightweight and or soft materials, compliant actuators, reacting to collisions through sensors and software and how the control architecture along with the dependability of a robot needs to be taken into account [47].

2.4 Existing Solutions

Driven by science fictions epos, such as Star Wars, people became familiar with the idea of having a faithful and entertaining robot companion. In 2015 the market for social and entertainment robots stood at 1 billion USD [48]. It is forecasted to grow to 1,38 billion USD by 2025. Sparked by this huge market potential, industry and science have enforced research in the field of social robotics. Today there exists a great variety of models. Various authors have created helpful overviews of existing social robots [49]. For the purpose of this study three different categories are examined: Human-like robots, animal-like robots and smaller tabletop robots. Starting with human- like robots, two examples are the Furhat (developed by former KTH students) [50] and the Pepper robot [51]. Both are shown in figure 2.5. While the Furhat robot only consist of a face the Pepper robot has a whole body with arms, legs, trunk and head. The face of the Pepper robot is reduced to two eyes and a mouth. The mouth is rigid and represented by a black dot or line. By showing familiar features, human-like robots help to establish a social relationship. On the other hand, there is a risk of with creating too many expectations. If a robot has legs and/or arms, one expects that the robot can walk and/or grab an object.

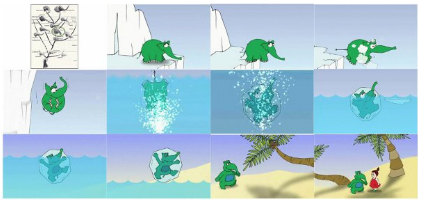
(a) The Furhat robot [50].



(b) The Pepper robot [51].

Figure 2.5. *Two examples of human-like social robots.*

Just as the anthropomorphism debate, there is also a zoomorphism debate. Zoomorphism describes the recognition of familiar animal body features and behaviors. Two examples of animal-like robots are the Probo (elefant) [52] and the Sony Aibo (dog) [53]. They are presented in figure 2.6. Probo is based on a comic design. However, translating the comic design into a mechanical design takes away some of its appeal (compare figure 2.6b). The Sony Aibo robot takes the role of a faithful companion. It strongly builds on the attributes connected to dogs (a human's best friend). Nonetheless, it should be pointed out that animals are not associated the same characteristics all around the world.



(a) Comic design of the Probo robot [52].

(b) Physical design of the Probo robot [54].

(c) The Aiboo robot [53].

Figure 2.6. *Two examples of animal-like social robots.*

Four examples of smaller table top robots are the Kuri, Jibo, Vector and Emo robot [55] [56] [57] (see figure 2.7. Usually these robots are designed to look cute. Surprisingly, many of them include the ability to dance (e.g. Jibo, Vector and Emo). However so far small social robots are waiting for their commercial breakthrough. In 2019 Jibo and Kuri failed in the market and in 2020 they were followed by Vector [58]. So what are the barriers? A big challenge is to deliver what people expect. Communication and movement of small table top robots are often neither flawless nor natural. Communication for example usually follows the scheme of one after another thereby ignoring spontaneous interruptions. While motion is used to express emotions it is not designed to help with physical tasks. These limited capabilities meet advanced prices. The prices for the basic Vector models start at 249 USD [57]. So people question if they really need the robot. Nonetheless, the story for Jibo and Vector continues. After their respective companies closed down, design and patents were acquired by other companies (Anki by Digital Dream Labs and Jibo by NTT Inc).

(a) Kuri robot [55].

(b) Jibo robot [56].

(c) Vector robot [57].

(d) Emo robot [59].

Figure 2.7. *Four examples of smaller table-top social robots.*

Two more examples of table top robots are presented in figure 2.8. These are the Keepon robot and a companion robot by Panasonic (without name). The Keepon is made of two balls which sit on top of a platform. It looks like a chick. Compared to other robots the Keepon robot consists of soft materials. The companion robot by Panasonic is an egg shaped robot. Its comes with the novelty that the upper part of the egg can be lifted. When doing so a moveable arm is exposed.

Going back to the requirements, it is stated that children will be the primary

(a) The Keepon robot [60].

(b) Panasonic companion robot [61].

Figure 2.8. *Two inspiring table top robots.*

target group for the robot. So how do children imagine a robot? Rincon et al. asked 19 children the question, what would be a robot they would like to play with [62]. The children described a robot with anthropomorphic features. Moreover, the children wanted the robot to be able to move, grab and speak as well as play popular children games. They also imagined the robot as being tough and strong. Some children drew a sketch. The robots sketched showed quadratic shapes and grey colour (metal resemblance). All robots also had arms and legs.

Moving on from the physical designs, further takeaways from existing solution have been found in the field of body language. McGoll et al. describe the development of an emotional body language for the human like social robot Brian [63]. Their findings stress the importance of viewing angle on the perceived emotional state. Furthermore, they provide body language descriptors for different emotions (e.g. Sadness: Bowing trunk, head forward, hanging arms and low movement dynamic). Another study on the expression of emotions is conducted by Takashi et al. [64]. The team developed a teddy bear robot that is able to express the six basic emotions. The respective motion design is based on the Laban movement analysis. One takeaway from this study is that emotions are not expressed as a static posture but rather as a dynamic movement. Further inspiration for the expression of emotions can be taken from animations and cartoons. Ribeiro et al. study different animations techniques and relate them to the design of an emotional body language for the EMYS robot [65]. Techniques include the ideas of exaggerations (e.g. eyes popping out, separating body parts) and follow-through movement (actions should not stop abruptly). A helpful point of reference are Disney's 12 design principles [66]. Instead of emotions Chatterjee et al. explore the question whether a robot arm can convey certain messages using only body language [67]. The messages examined in the study were: The robot saying hi, not disturb, act in a friendly manner, and act in a machine-like manner. The idea of conveying messages additional to emotions will be considered in the design.

Chapter 3

Concept Design

Based the research, potential designs of the robot could be explored. This was an iterative process where research, sketches and mock-up 3D-models were made in parallel. Sketches have been refined with increasing knowledge in different research areas. The stakeholder requirements were also taken into account when the design ideas were being developed. From all the design ideas, three concepts were formulated. The three concepts can be referred to as the egg, the improved Haru and the snowman. When developing the improved Haru concept it became clear that the improvements from the earlier model were not enough. In addition, when the concepts were being presented to the stakeholder, we got the information that these improvements were already being done by another team. What he wanted from the team was instead a new and novel concept. It was therefore decided to not move forward with this concept. Instead, focus was on improving the egg and the snowman concept. A more comprehensive description about the concepts, the technical challenges and the expression capabilities are presented below.

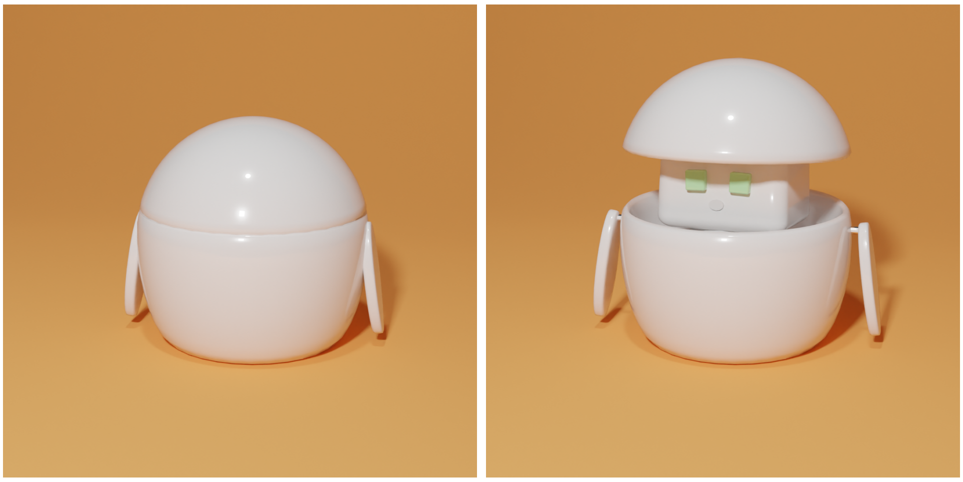
3.1 UNICEFs Policy on AI for Children

Robots are getting more advanced and introduced into our lives, not only as labor robots but as social-companion robots. In order for this transition to succed robots need to be designed trustworthy because otherwise, users would not interact with them. When talking about users, all potential stakeholders need to be considered. Here children are identified as the most vulnerable group. To help developers in the process guidelines exist. UNICEFs guidelines are one of them. The four most important points they stress for a trustworthy and safe interaction are:

- Safety: In terms of both physical and non-physical.
- Transparency: A user needs to know: ”When am I recorded?”, ”Is any of my data stored?”, ”Is the robot connected to the internet?”.
- Reliability: The robot should be able to run for several hours without breaking.

- Explainability: A user needs to know: ”What can the robot do?”, ”Why did a robot act the way it did?”.

3.2 Egg



(a) Closed *(b) Open*

Figure 3.1. *Concept renders of the egg. Made with Blender* [68]

The egg concept was based on the idea that the robot would look like an egg when closed. This can be seen in figure 3.1. When in a closed state the robot clearly indicates that it is not in use, therefore fulfilling the requirement of providing transparency to the user. It is also structurally a very strong shape with no sharp edges. This protects both the robot and the child using it, ensuring safe operation. When active and in the ”open” position the robot can:

1. Move head up and down.
2. Tilt head back and forth (within a limited range).
3. Rotate head.
4. Extend/retract arms.
5. Rotate arms up and down.
6. Rotate eyes.
7. Rotate base.

3.2.1 Patent Infringement

To ensure that the concept designs do not infringe on any existing patents or designs, a patent infringement check was made. Since the Egg robot was inspired by Panasonic's Desktop "Companion" Robot [61], this was checked first. Here it was concluded that the Egg concept was not infringing on any existing patents that would be of risk for future work. Further design patents were checked and none were found to be a risk of the Egg design.

3.2.2 Technical Challenges and Simplifications

The main challenge with the egg robot is to fit everything inside the "egg" (body of the robot). This has been researched and found that motors with sufficiently good size/strength ratios are available to fit the need of this project. For the above motions the following solutions have been proposed followed by figure 3.2 to further demonstrate:

1. **Move head up and down**: Using a threaded rod mounted at the bottom, driven by a DC-motor.
2. **Tilt head back and forth** (within a limited range): DC motor mounted at the neck of the robot.
3. **Rotate head**: DC motor mounted in between threaded rod and tilt motor.
4. **Extend/retract arms**: Using rack and pinion mechanism.
5. **Rotate arms up and down**: DC motor mounted on the rack on pinion mechanism.
6. **Rotate eyes**: DC motor inside the head.
7. **Rotate base**: DC-motor connected by a rubber belt.

Another challenge is to make sure the robot is not able to cause any harm to a child. This can be achieved by using compliant motors. Therefore if the robot closes but a child's hand is in between it would comply and not hurt the child. The arms could use the same mechanism but could also be made from a soft material, increasing safety even further.

3.2.3 Expression Capability

Using the six movements described above the robot can express emotion as seen in figure 3.3. Other possibilities include graphics or colours on the eyes which would further improve the capabilities of this concept. Sound is also being explored in addition to the movement.

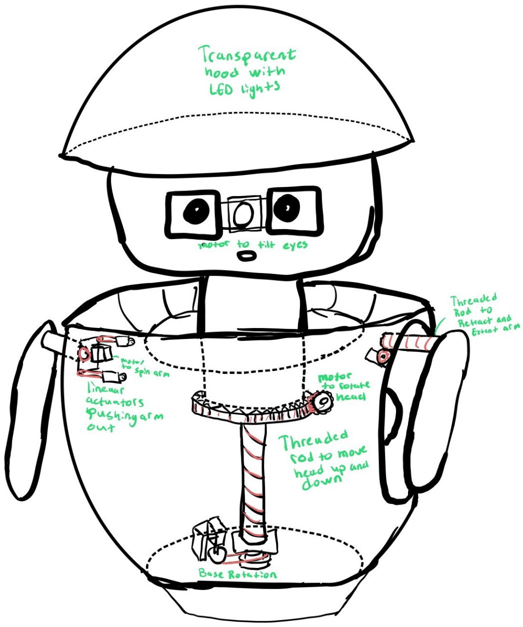


Figure 3.2. *Sketch to illustrate technical aspects of the Egg concept.*

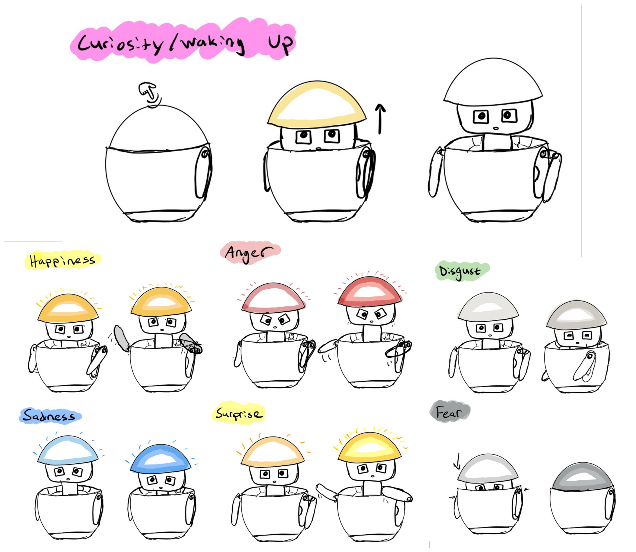
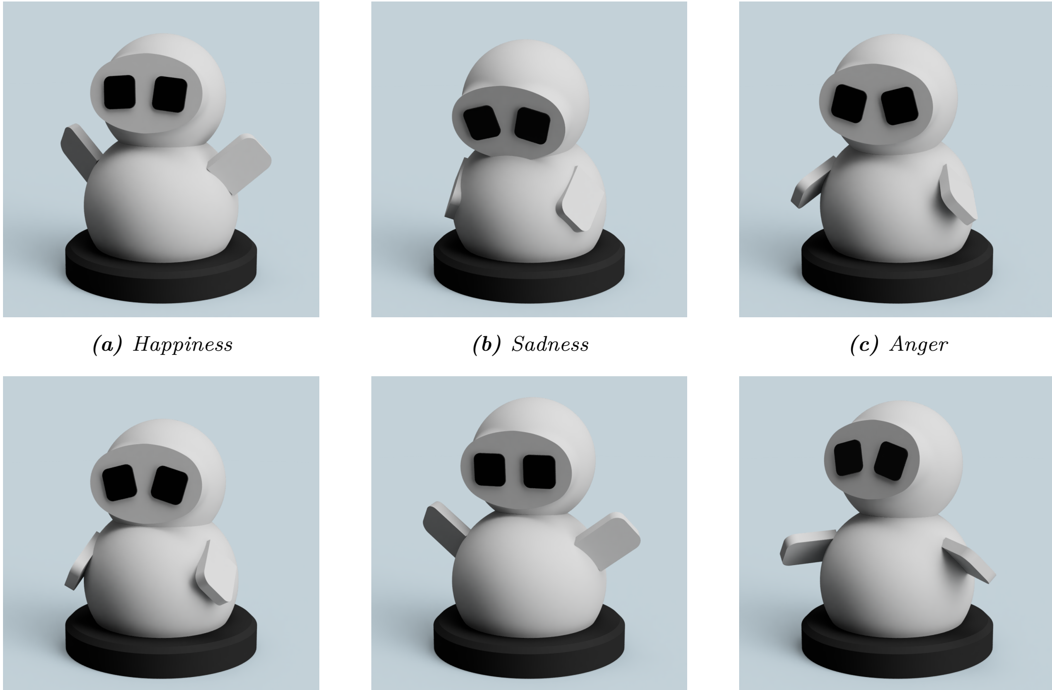


Figure 3.3. *Sketches on how the Egg concept expresses emotions..*

3.3 Snowman

Named after its appearance, the Snowman concept consists of a spherical head mounted on a larger spherical body with two simple arms. The preexisting Keepon robot served as the main design inspiration [70][60]. While being similar in appearance, the snowman is mechanically quite different. To effectively express emotions,



(a) *Happiness* ***(b)*** *Sadness* ***(c)*** *Anger*

(d) *Fear* ***(e)*** *Surprise* ***(f)*** *Disgust*

Figure 3.4. *Concept renders of the snowman expressing the six basic emotions. Made with Autodesk Fusion 360[69].*

the four Degrees of Freedom present in Keepon were not deemed enough. Instead the snowman was envisioned with eight or nine DoF, depending on if the two arms are controlled individually or not. The possible movements are full positional control of the head in three dimensions (6 DoF), rotation of the eyes (1 DoF), and finally raising and lowering of the arms (1 or 2 DoF).

Since detailed facial motions could pose a large challenge to fit into a smaller robot, the design process started by primarily looking at body language instead of focusing on facial expressions. Creating an expressive mouth would for example be challenging if more detail than opened/closed was desired. Drawing inspiration from the passive body of Keepon, only the head of the snowman is actuated actively, with a soft body following passively. To improve the expression capability as compared to Keepon, the concept was envisioned with a stewart platform inside the body to freely position the head within it's range of motion [71]. This allows for the illusion of separate spine and neck joints, while having all the actuators seated on the base.

Since having only the head and body was still not deemed sufficiently expressive, the arms and rotating eyes were added. While the head could be shifted and rotated to express some emotions such as sadness, others such as surprise and happiness were hard to distinguish for us in the team. The arms add an easy way to express directionality and can also exaggerate the motion of the head. By rotating and simulating brow movement, the eyes enable the concept to show more subtle facial cues that can help a viewer distinguish between emotions such as happiness and surprise (see figure 3.4).

The actuation of the arms is a challenge with the arms being mounted on a soft body, with the joints following the body movement. The simplest solution could also be to mount the actuator to the body and to have a rigid assembly of arm and motor moving together. This could add a significant amount of weight to the body, potentially deforming it, and more importantly might interfere with the stewart platform linkage inside. The more complex and more promising option is to cable actuate the arms, this way the motor could be situated in the base with only a flexible cable attached to the arm joint, not hindering it from moving with the body. Specifically, a bowden tube and cable would be used to actuate the arm, enabling actuation without exerting a force on the body itself. Construction was imagined similar to that of a classic bicycle brake caliper, with a mount taking the reaction force of the actuation (see figure 3.5 below).

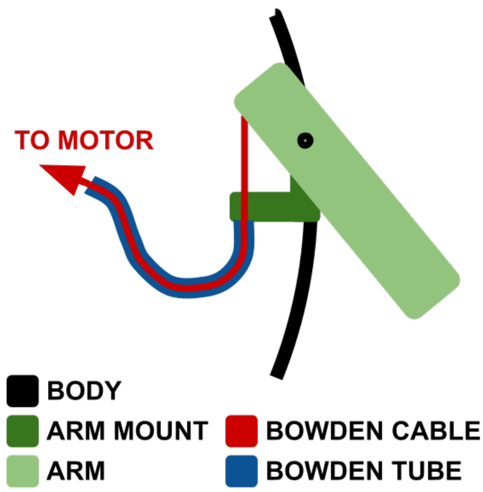


Figure 3.5. *Proposed construction of the arm mechanism for the snowman concept.*

3.3.1 Patent Infringement

Since the design of the snowman concept was heavily inspired by the *Keepon* robot [70][60], possible patent infringement was checked carefully and no related patents could be found.

3.3.2 Technical Challenges and Simplifications

As envisioned, the snowman concept uses a steward platform to position the head, with a soft body that deforms and follows the head motion. This way, you can achieve the illusion of separate body and head joints, while having all the motors stationary in the base. In addition, the two arms are fastened to the soft body and must be actuated. The concept therefore faces three major technical challenges.

1. Can the linkages required for the stewart platform fit inside the body while providing adequate range of motion?

2. Are there actuators with sufficient power to both fit inside the body and drive the head motion properly?

3. How can one actuate arms that are attached to a soft body without interfering with the body motion?

Chapter 4

Methodology

In the first part of this project a literature study was conducted. The research explored different topics including the modelling of emotions and HRI. The knowledge was then used to create different concept designs. This methodology section now introduces the second phase of the project. First of all a final concept design had to be chosen. Then the chosen concept design had to be refined into a working prototype. Among others, the measurements and placements of components had to be estimated. Afterward the mechanical design as well as software and electronics were implemented. In the end the robot was validated and results presented.

4.1 Concept Design and Evaluation

Following the SOTA review and the requirements, the two concepts ”Egg” and ”Snowman” were developed as presented in section 3.2 and 3.3 respectively. The team initially developed an evaluation table as shown in Appendix D. For each concept the evaluation table considered different technical obstacles and solutions, expressiveness in terms of design and motion as well as potential for further development. Finally, the group made a decision by first discussing the various requirements in the evaluation table and then voting on a preferred concept. The concept ”Egg” was considered to be the most suitable for the purpose. In addition, the choice was also confirmed by a discussion with our stakeholder who had the same opinion.

4.2 Design Process

The requirements provided upper limits for the dimensions of the overall height and base diameter. In order to determine the optimal size and shape of body and head the group created cut-board models and 3D sketches. After comparing the models, the most desired features of each model were taken and combined into a single one, giving approximate dimensions to follow in the later design work. In a next step, sketches were made to determine possible designs of each subsystem. Finally, the first version of the mechanical design was started.

The mechanical design process started by dividing the robot into different sub-systems in order to better manage specific solutions and to achieve a balanced work-load. Four sub-systems were created which are the base, neck, head and arms. For each subsystem, different solutions were brainstormed and thereafter represented in a morphological chart (see appendix E). The morphological chart was then used to combine solutions for each subsystem into one solution for the entire system. Each subsystem included suggestions for different components, degrees of freedom and estimations of torques and loads. This was an iterative process, cycling between developing motion mechanisms, (estimating torques) and choosing components.

From the many solutions three final ones were chosen and presented to the stakeholder. The solutions were designed based on the cost of components (low cost, compromise and quality option (see appendix E). In the end, a mix of the three options was chosen. Given the selection, all the necessary components was able to be ordered. At the same time, the process of creating a detailed Computer Aided Design (CAD) model started. The placement of components was either determined by design restrictions or decided experimentally. For example different CAD model were created to determine the optimal position of the eyes in the head. After optimizing the CAD model in terms of placement, space and motion range, the 3D printing process started. It was decided to use 3D printing both due to availability and low cost. Furthermore, the number of metal components inside the robot was wanted to be reduced. Finally the 3D printed components were mounted together and combined with the electrical components in order to create a final prototype. For a final bill of materials of the CAD prototype, see appendix F.2.

4.3 Electronics and Software

The electronics and software planning process started simultaneously with the concept design process. It included decisions on which sensors were necessary for the robot to interact with its environment and later what electronic hardware would be required to program the robot. An important part of the software development was the idea of software modularization. Having different modules (i.e. for computer vision, motion control and sensor input) enabled the group to split up the work and develop different modules in parallel. Furthermore, having separate modules facilitated isolated debugging and troubleshooting, while also providing better expandability. To keep the modules organized flow charts were used to represent hierarchies and set-ups. Other questions related to software were the choice of an operating system for the main controller (Linux or Windows) and programming language (Python or C++). To foster the learning process it was decided to use Linux and C++. The idea of modularization was also implemented for electronic hardware. For example, it was decided to use separate microcontrollers for graphics and sound. All sub-modules were connected to the main control unit. An important step was also the creation of a circuit diagram in order to wire the components without errors risking hardware damage.

4.4 Verification and Validation

Verification and validation of the work is necessary in order to check the requirements set by the stakeholder. Verification is concerned with meeting the design specification while validation deals with meeting the operational needs of the user. Both help to identify the capabilities as well as weaknesses of the system. For our project it was necessary to prove the technical reliability of the robot as as well its expressiveness capability.

Firstly, testing the reliability of a system could be done by repeating a set of motions for a predefined duration. Points of interest during the test are internal temperatures, motion irregularities and noise. In the end it was decided together with the stakeholder to run a reliability test of at least four hours. During the test, temperature of the motors are logged and images of the inside of the robot are regularly taken using a thermal camera. Finally, the noise level of the robot is measured using a mobile application.

Secondly, investigation the expressiveness requires qualitative research methodologies. A variety of methods exists such as interviews, focus group discussions, participant observations or questionnaires. While for example a focus group discussion or demonstration at a school would deliver first hand information it also requires an ethical approval which is both time and cost intensive. Therefore it was decided to create a questionnaire.

Chapter 5

Implementation

This chapter presents the implementation process of the egg concept into a physical prototype. This tabletop robot is in its non-use state, fully closed. This creates an excitement and curiosity about what's inside and how a user will be able to interact with the robot. When interacted with, it opens up with the arms coming out and the head popping up. The robot is then able to track a person in its environment and express the six basic emotions. The robot in its closed and opened state is seen in figure 5.1. Following the Egg concepts, the only motion that the final prototype is not able to achieve is the rotation of the head. This was deemed by the stakeholder and the group to be a too complex implementation and would be difficult to fit inside of the shell. Additionally, an extra DoF has been implemented in the arms so that they can tilt outwards and inwards to achieve a more natural arm motion. This was implemented following a request from the stakeholder. The actual mechanical mechanism of how all the motions are done has also been changed and is now presented in the following sections.

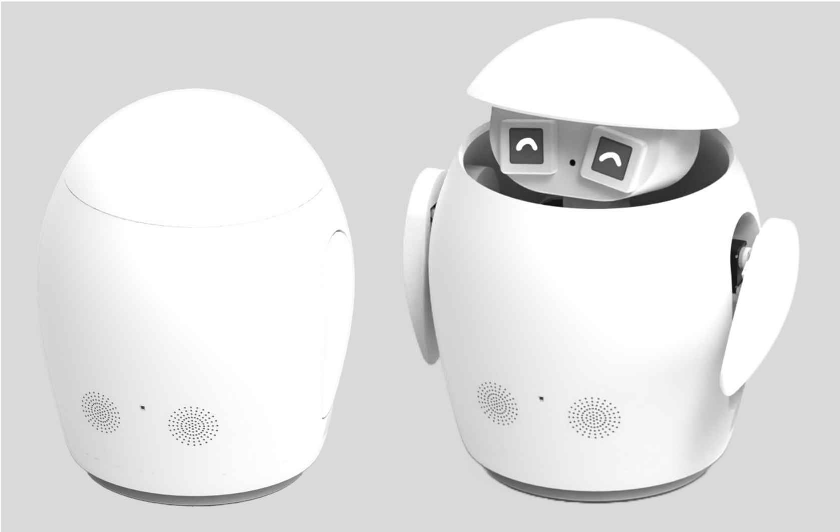


Figure 5.1. *The robot in its closed and opened state. Made in Keyshot.*

5.1 Mechanics

Following the egg concept, the mechanical design of the robot was divided into four subsystems; the base, the neck, the arms and the head, see figure 5.2. For the robot to work as described, it utilizes 11 DoF as shown in figure 5.3. This enables it to express emotions through both body language and facial expressions based upon findings from the SOTA.

Torque calculations were done on critical parts such as the neck lifting mechanism. Based on the calculations, space limitations and the desired visual design, a 3D-model of each subsystem was developed in Solid Edge[72]. The digital design was then realized using Fused Filament Fabrication (FDM) 3D-printing and assembled. In this section, the mechanical implementation of each subsystem is presented. In addition to the subsystems, a shell was made to fit all the mechanical and electrical components and to provide the desired look.

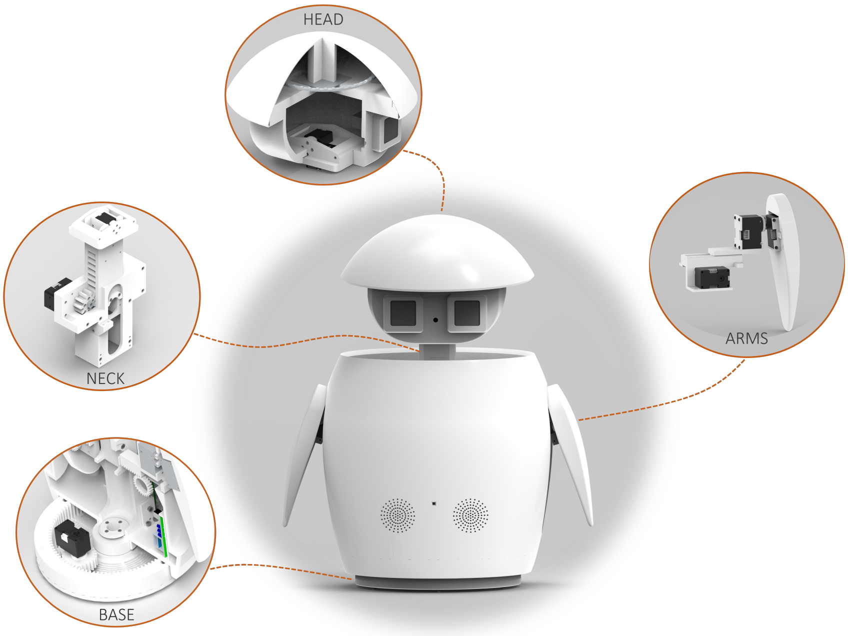


Figure 5.2. *An overview of all the mechanical subsystems. Made in Keyshot and PowerPoint.*

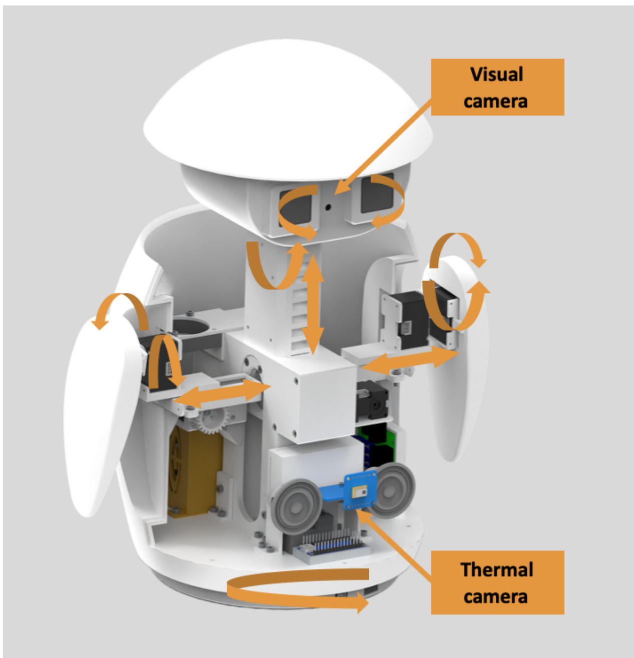


Figure 5.3. *The robot has eleven DOF. It can see its environment with a visual and a thermal camera. Made in Keyshot.*

5.1.1 Subsystem - Base

To enable the robot to rotate its body, an internal gear was implemented in the base with a tapered roller bearing in between to enable low-friction motion. This is seen in figure 5.4. To lock this mechanism in place so that the robot does not come apart when lifted up, a locking plate is placed in the center to keep the base in place. A hole going through the middle of the base and bearing is used to route a power cable to the electrical components mounted inside the body.

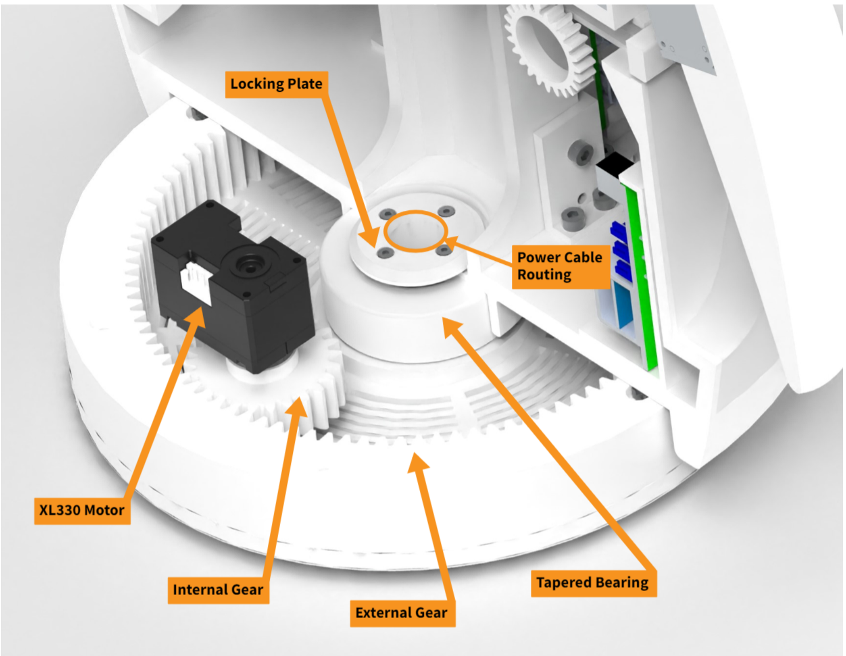


Figure 5.4. *The base rotation mechanism. Made in Keyshot.*

5.1.2 Subsystem - Neck

Being critical for the robot concept, a lot of thought went into the design of the neck assembly, starting from the requirements of the head extension actuator. With space being limited inside the robot, the requirements for the neck sub-assembly set during design were:

1. The actuator must be able to lift the head weight, estimated to be 1kg.
2. The actuator must have some force sensing capability to detect potential pinching of limbs and be able to provide emergency stop functionality.
3. The travel must be at least 70mm.
4. The actuator has roughly 140mm of vertical space available underneath the head when the robot is closed.

On the top level, three different designs were considered to fulfill the requirements. The first option was to use an off-the-shelf linear actuator, but no models that would fit inside the robot, while still having sufficient force, stroke and force sensing, were available. This left the two other concepts, a leadscrew as envisioned in the original egg concept and a rack and pinion based design. In the end, a rack and pinion was chosen for easier backdriveability (safer in a pinching scenario) and also the fact that a leadscrew design would have to include some motor or rotation transfer component on the bottom of the rod taking up precious vertical space. By choosing a rack and pinion, the full vertical space could be used for the ”slider”, with the driving motor mounted to the stationary ”tube”.

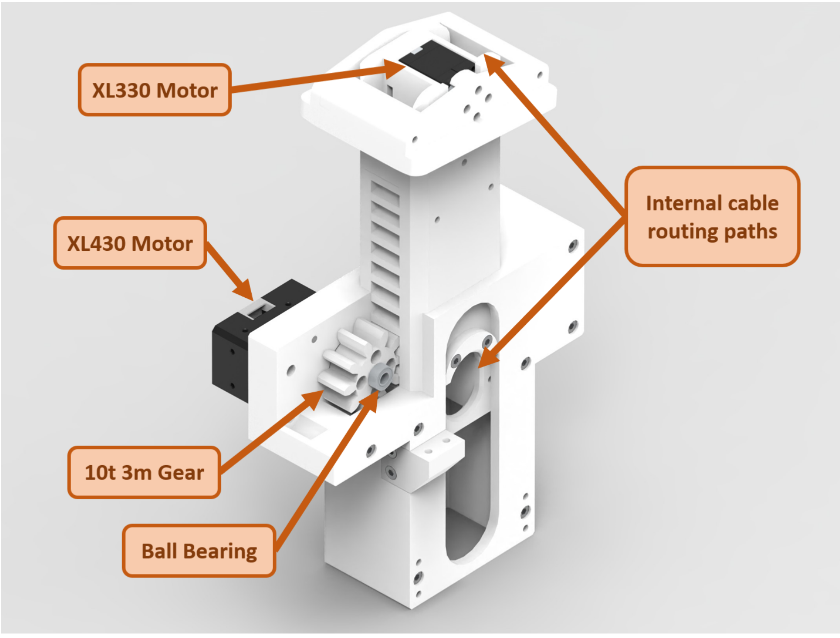


Figure 5.5. *The neck subassembly with a partial section view showing the internal gear. Render made in Keyshot.*

In the final design which is seen in figure 5.5, a Dynamixel XL430-250-T servo is used to drive the neck extension. Torque is transferred through a 10-tooth, module three pinion, with a passive pinion and rack supporting the neck on the opposite side of the slider. The free ends of the gear axles (all ends except the one mounted to the motor) are mounted in 10x5x4 bearings to reduce friction and noise. At 12V and the chosen gearing, the motor is according to spec and Dynamixel recommendations capable of generating 20N of dynamic lifting force, sufficient for the application [73][74].

$$(1.5Nm * 0.2) \,/\, (0.03m * 10/2) = 20N \tag{5.1}$$

The torque required is the reason that the smaller and cheaper XL330 motors used elsewhere were not used in the neck. From their stall torque of 0.6Nm (which is less than 1.5Nm*20/10), it is quick to see that one motor would not provide the sufficient force with the same gearing [75]. To achieve the required torque, the smaller gear would have to have eight teeth.

$$10teeth * (20N/10N) * (0.6Nm/1.5Nm) = 8teeth \tag{5.2}$$

This would however result in a gear root diameter so small that mounting it to the motor could prove difficult. For ease of mounting and to have a safety margin, the bigger motor was therefore chosen.

Also worth noting is the internals of the neck assembly. To allow cable routing to the head, the neck is hollow with cable access from both sides and downwards. In the top of the neck, the head nodding motor is also mounted with its' wires routed down through the neck.

5.1.3 Subsystem - Head

From the State-of-the-Art, it was clear that the eyes play a big part in expressing emotions, it was therefore important to be able to express the six basic emotions with help of the eyes that are mounted on the head. To show emotions with the eyes, a quadratic shape of the cases was chosen, to easier enhance the different states of the eyes, see figure 5.6. Displays are positioned inside the cases. This is then connected to a motor that is placed on the inside of the head, see figure 5.7. The motors' function is to rotate the case to the desired position connected to a specific emotion. Since the rotation is simple and the load is small, two SG90-motors were selected. The head also contains the camera that is used for tracking a person, see Chapter 5.3.4 for more information. It is placed between the eyes with a small hole for the lens to see through. The idea behind the placement of the camera is that it should provide transparency and safety for the user. When the robot is closed it is also clear to the user that they are not being recorded.

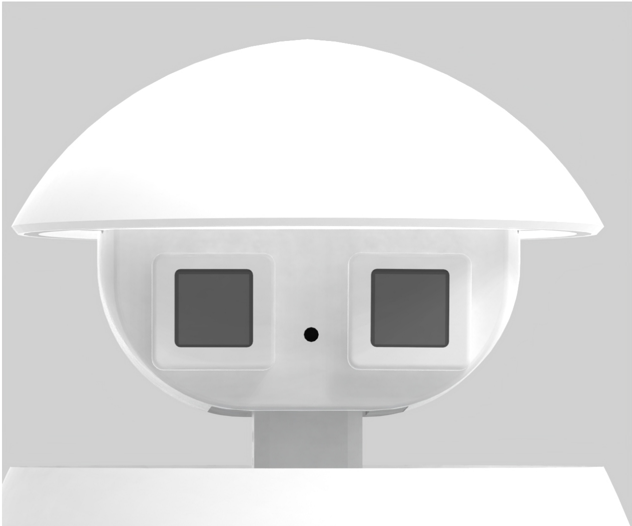


Figure 5.6. *Head with mounted eyes and hole for camera. Render made in Keyshot*

The head is divided into two parts, so it is possible to disassemble the hat from the head. Inside the hat a force sensitive resistor is placed, the hat design contains a pillar that goes down to the force sensitive resistor see figure 5.7, this is connected to the waking up motion of the robot. When the robot is closed and someone pushes down on the hat this is registered by the force sensitive resistor, and the robot wakes up. From the SOTA, it is stated that colours could be used to enhance the emotion, therefore a Light Emitting Diode (LED)-ring has been placed in the hat. The LED-ring will light up in different colours depending on the emotion the robot expresses.

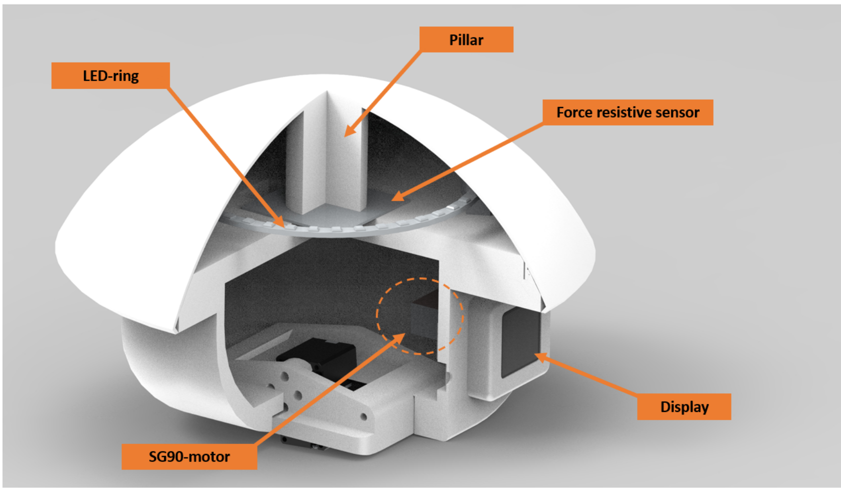


Figure 5.7. *Cut out of the head. Render made in Keyshot*

5.1.4 Subsystem - Arms

The mechanical design of the arm can be seen in figure 5.8. The mechanism consists of three smart servo motors giving the arms three degrees of freedom. Motor number five pushes the arm out of the body with help of a rack and pinion. Motor six enables a 360 degrees rotation of the arm. A flapping motion is created with motor seven. Motor number five and six are placed at the same height, giving the arm a natural, shoulder-like, motion.

Figure 5.8. *An overview of the arm mechanism with its different components. Made in Keyshot.*

5.1.5 Shell

The shell is made to realize the desired design of the robot. In addition to design, the shell also brings functionality. It protects all the internal electrical components and also reduces the sound level of the robot. Moreover, it contains mountings for the subsystems, bringing the whole mechanical design together. The base is mounted from the bottom and the arms are mounted from above, see figure 5.9. Mountings for the speakers are provided in the front and the small holes allow the sound from the speakers to come out from the body. A thermal camera can be mounted between the two speakers.

For the sake of manufacturing and mounting, the body is divided into two. The 3D-printer provided in the project could only fit one half of the shell. Being able to split the body also ease when mounting all the components and when testing the software.

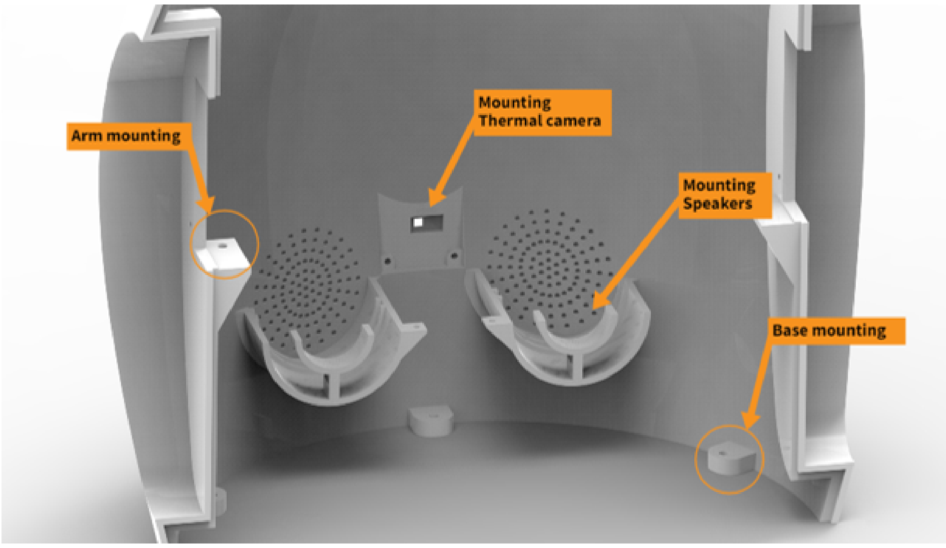


Figure 5.9. *The inside of the shell with all the mountings. Made in Keyshot and Power Point.*

5.2 Electronics

The planning process and development of the electronics part of the system began shortly after the initialization of the mechanical design, after deciding on all the components needed for the robot. Similar to the mechanics, the electronics was divided into four main subsystems. Figure 5.10 shows an overall representation of each subsystem. A Teensy microcontroller is used to control the LED-ring with the colours, the motion and graphics of the two LCD screens, and the press sensor (force sensitive resistor) used to wake the robot. Furthermore, an Arduino Nano is used to control the two speakers and the thermal camera located in the body (see figure 5.3). The robot's movements are controlled by Dynamixel servo motors, eight of type XL330 and one of XL430, driven by a motor driver called U2D2. These parts, along with the camera in the head, are connected to a single board computer called UP Core that contains the main code and is responsible for the cooperation between the different subsystems. All subsystems are communicating with the UP Core through serial communication using Universal Serial Bus (USB) protocol, except the Dynamixel servos using Transistor-Transistor Logic (TTL) protocol.

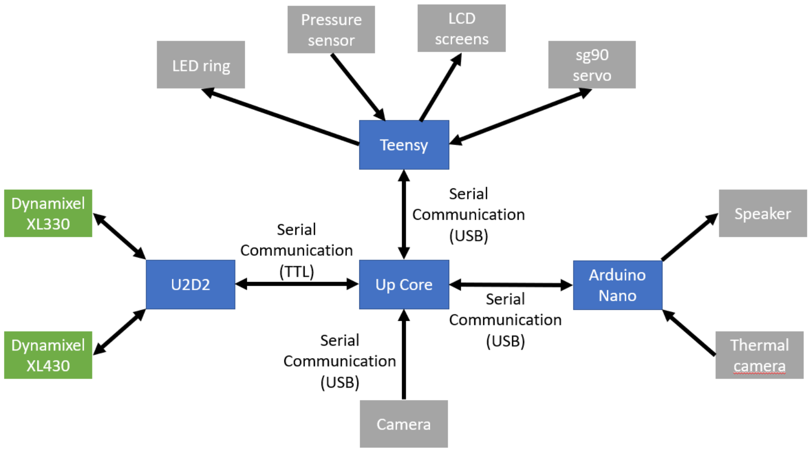


Figure 5.10. *Overview of electronics components in the robot. Made in PowerPoint.*

In addition to the parts mentioned above, there are also two fans, a DC-DC boost converter, a Bi-directional Logic Level Converter and a stereo amplifier. All the robot components require a voltage level of 5 volts, except for the Dynamixel servo XL430 which actuates the head and one of the fans responsible for conducting heat out of the body. These require a voltage level of 12 volts and this is where the boost converter is used. The Bi-directional Logic Level Converter is also used with the Dynamixel XL430, since the signal level of this servo is higher, and it assures the avoidance of too high signals in the XL330 servos. See the detailed electrical diagram in figure 5.11

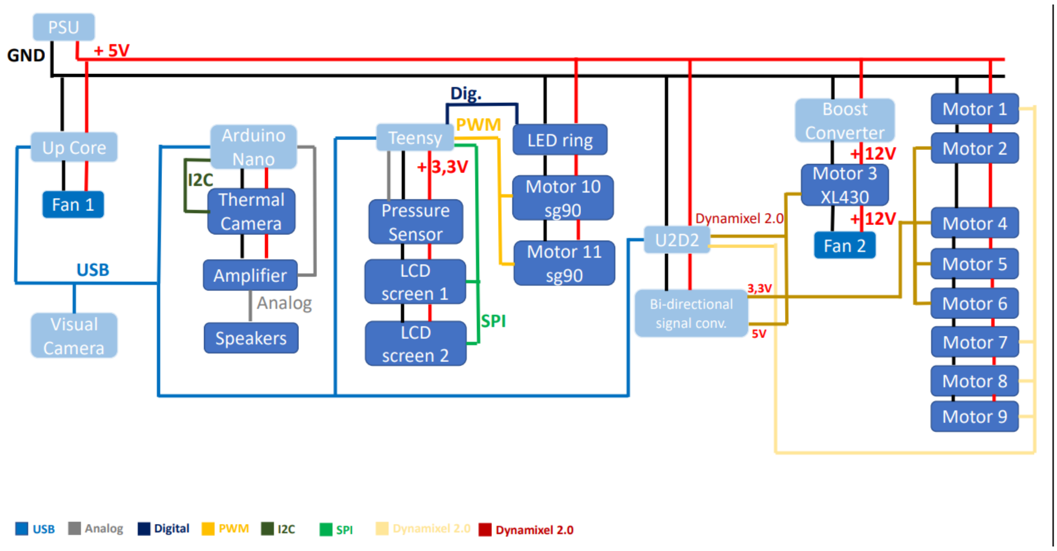


Figure 5.11. *Detailed description of electrical components and their connections. Made in PowerPoint.*

5.2.1 Actuators

Due to the intended environment of the robot and the mentioned requirements for safety and reliability, it was important to choose actuators that can match the expectations. The Dynamixel motors, XL330 and XL430, from the company ROBOTIS were chosen not only for their reliability but also because they have compliance capabilities [75][73]. This means that they facilitated the trajectory planning and control of the body movements since they provide the ability to be connected in series. These types of actuators are also called smart actuators, which means that in addition to a DC motor and reduction gears, they also include a controller, a driver and integrated sensors. The ability to get values for current, voltage, position, and temperature, reduces the complexity of the system immediately due to the reduced amount of external sensors needed. The current sensor could be directly connected to the safety requirements since it enables adaption of the current and torque limits, which means that the user runs no risk of getting stuck between the open parts of the robot.

The motors used for the screen movement, simulating eyebrows movement, are cheap SG90 servos. Since the screens only can rotate and do not move out from the head, the safety requirements are less critical in this part of the robot and therefore using closed loop servos was considered sufficient. These motors are controlled through PWM signals.

5.2.2 Sensors and Interaction

As introduced in previous sections the system includes various components for sensing and interacting as listed in table 5.1. The vision camera is easily connected via

Table 5.1. *Table of the sensing and interaction of the robot.*

Sensing	Interaction
Visual camera	1.3 inch screens
Thermal camera	Speakers
Force sensitive resistor	LED Ring

USB to the UP Core. The thermal camera uses an I2C interface while the screens use an SPI interface. An SD card reader is directly connected to the back of the screens. For the connection an additional pin is necessary. Generally, all non USB connections are directly soldered. To wake up the robot a force sensitive resistor is used. The sensor sits inside the head. The way the sensor works is that depending on the force it is pressed with its resistance decreases. An analog pin on the Teensy is used to read the resulting voltage change. Additionally, a 5Kohm pull-down resistor is used to get stable readings. For the speakers a stereo amplifier is implemented. The amplifier sits between the Arduino Nano and the speakers. Finally, the LED ring comes with an RGB chip and hence allows for precise color control.

5.3 Software

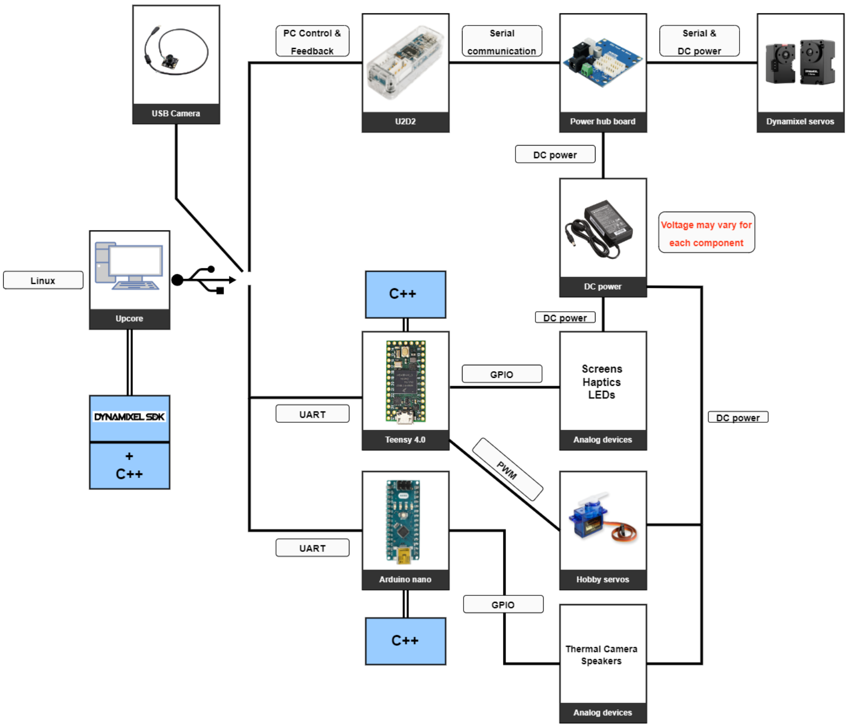
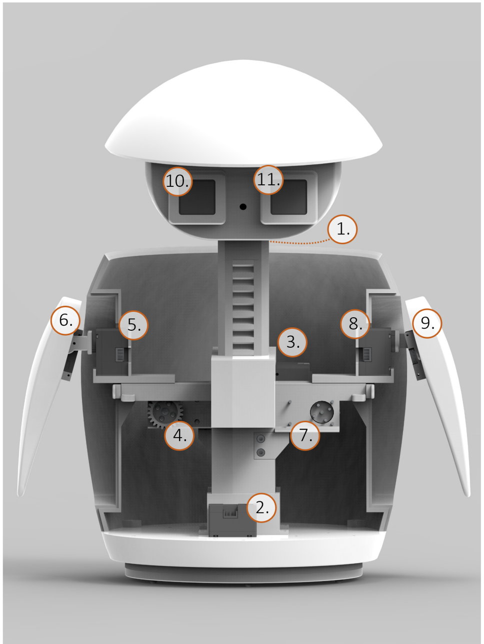


Figure 5.12. *Software diagram*

The software for the robot is written entirely in C++ and utilizes many different libraries and packages to fulfill different functions. The software is distributed and running on the three processors to coordinate different tasks and achieve overall robot function. This can be seen in figure 5.12 above. The reasoning behind the distributed system is that it allows offloading of processor-intensive/real-time tasks such as display driving or audio playback from the main processor. As stated in the previous sections, a total of three processors were used. The main processor is an UP Core, a single-board computer with Ubuntu 22.04 installed. The UP Core commands the function of the two slave microcontrollers one Arduino Nano and one Teensy 4.0. The inter-processor communication is done via USB, using a custom serial message protocol. Programming of the microcontrollers was performed utilizing the Arduino IDE [76], with the teensyduino extension for Teensy compatibility [77]. Appendix G.4 is a summary of the processors and their performed tasks.

5.3.1 Motion Control



ID	MOTION	MOTOR TYPE
1	Neck nod	Dynamixel XL330
2	Base rotation	Dynamixel XL330
3	Neck extension	Dynamixel XL430
4	Arm extension Right	Dynamixel XL330
5	Arm rotation Right	Dynamixel XL330
6	Arm pitch Right	Dynamixel XL330
7	Arm extension Left	Dynamixel XL330
8	Arm rotation Left	Dynamixel XL330
9	Arm pitch Left	Dynamixel XL330
10	Eye rotation Right	SG90
11	Eye rotation Left	SG90

Figure 5.13. *All the motors with their corresponding ID and motion. Made in PowerPoint.*

The mechanical design of the robot creates limitations for the position of the motors. Position limits for each motor are therefore implemented in order to not break components. To reach the requirement of showing the six basic emotions, the motors need to be controlled to different goal positions depending on the emotion. A keyframe is made for each emotion. The keyframe contains information to control the dynamixel motors, the SG90-motors in the eyes, the LED-ring and commands to control the screens. All the motors and their position can be seen in figure 5.13, besides that, the LED-ring is placed in the head and the screens in the eyes.

For the LED-ring, a pre-defined colour is set based on the emotion. For the screens, different pre-defined images are shown, depending on what number is stated in the keyframe. The SG90-motors have a range of -200 to 200 where zero is the neutral position. For the dynamixel motors, the goal positions are given in encoder values. Each motor have different goal positions depending on the emotion. The goal position is connected to a tick. For instance, if the goal position is 2000:5, the motor will start to reach encoder value 2000 at tick 5 where the tick is set to 250 ms. The code also support velocity control. The speed is set individual on each motor to make a motion that enhance the desired emotion. The position and velocity control of the motors could be further investigated to find the sweet spot were the motions look more natural.

All the emotions are defined according to research done in the SOTA, see apenidx A.

5.3.2 Sensor and Interaction Drivers

As described in the previous section, the main motion control was coded using the dynamixel SDK. There are however several other components such as sensors and displays that require specialized software to use. This section goes through these components and briefly explains the software used to drive them. A summary of all libraries used is included in appendix G.1.

Starting with the LED-ring in the head, the ”FastLED” library by Daniel Garcia was used [78] This library provides easy control over the addressable LED-ring while having support for many different types of LED chip. This means that changing components requires minimal changes in the software. Note the teensyduio version of the library is needed for it to function properly on the Teensy processor, the normal Arduino version does not work properly. Implemented and used are a set of predefined colours, setting the colours of all the LEDs, but full RGB control of each individual LEDs is possible with minor modifications to the code.

Next up is the thermal camera, the model used was a AMG8833 from adafruit and the library used was their own ”AMG88xx” library. This provides easy to thermal image reading and uses the Arduino ”Wire” library for i2c communication with the camera.

To control the eye subassemblies, there are several functions needed. The rotation of the SG90 servo motors are controlled using the Arduino ”Servo” library (teensyduino port)[79]. Driving the displays require both reading the SD card and sending data to the screens. The communication to these components is done over SPI with the ”SPI” library and reading the SD card was done with the ”SD” library [80][81], both included in teensyduino. Driving the displays is a more demanding task and used was the teensy-optimized library ”ST7735_t3” by Paul Stoffregen [82]. It is based on Adafruits ”Adafruit_GFX” library so that was also used [83]. These libraries together made it simple to display bitmaps and can also be used to draw simple graphics such as lines, circles etc. All bitmaps defined and currently usable on the eye displays can be seen in appendix G.3.

5.3.3 Serial Communication

Vital for robot functionality is the communication between the as main processor and its slave micro-controllers, allowing the UP Core to control peripheral devices such as the LEDs. Implemented is a custom serial protocol that sends packets of data along with a tag signaling the type of message. The protocol is constructed in a way to be easily modified and expanded if further functionality is required in the future. Sending and reading data from the serial port is done through the library CppLinuxSerial by gbmhunter on the UP Core and the Arduino Serial library on the slave processors [84][85].

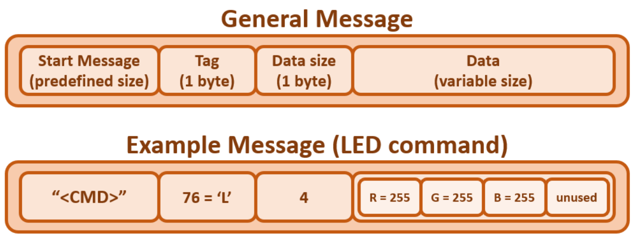


Figure 5.14. *Figure showing the general structure of a serial message and a specific example. Made in PowerPoint.*

A message packet consists of four parts (see figure 5.14), first a string of characters signifying the start of a message, then the message tag, the data size in bytes, and lastly the data. Both master and slave controllers check the serial buffer continuously and if the start string is matched, the following command is read and executed. A start string was chosen instead of the more common start character to make the communication more robust to errors and accidental messages if other characters are sent on the port. By also sending the size of the incoming data before the data itself, any data can be sent without issue. A common approach is to assign an end of message character to signify the end of a message, but this makes sending that particular byte of data impossible as it would be read as the message end instead of data. As it was expected to send all possible bytes of data (an RGB channel for the LED takes all values 0-255), preceding the data with the number of bytes to read was implemented instead. To prevent any accidental commands and errors, several safety checks are made for any received message. Firstly, the start message is needed, preventing accidental commands if other data is sent over the serial port (for example debug messages from the microcontrollers). Secondly, the data tag must be defined and valid on the receiving end (i.e. the Arduino will not handle commands with tags meant for the Teensy if they are sent over the wrong port). Thirdly, the size of the data must match a predefined value for each message tag. If it does not match, nothing is executed to prevent any errors from reading bytes as the wrong type of data. In appendix G.2 is a summary of all serial commands defined and implemented in the robot, and their respective data structure.

5.3.4 Tracking a Person

To satisfy the soft requirement of the robot being able to track a person in its surroundings. The computer vision library Open Source Computer Vision Library (OpenCV) was used [86]. The library provides free-to-use computer vision and machine learning software along with pre-trained models for object- and face detection. Face detection using Haar feature-based cascade classifiers is implemented for this project. The algorithm uses a lot of positive images (images of faces) and negative images (images without faces) to train the classifier. From these images, the most important features are extracted and weighted to find the best threshold which will classify the faces as positive and negative. From the paper, it has been shown to have an accuracy of 95% which was deemed good enough for this project [87].

For the implementation of this network to fit the purpose of tracking a person in the frame of a camera. All faces in the video stream are found and the position in the camera grid is saved. Additionally, an assumption that the biggest face i.e with the biggest radius when detected, is the one closest to the robot and should be looked at. This is done by dividing the frame into different sections. If the face is in the middle section no movement is needed. If a person is to the left or right of the middle frame the robot will rotate its base accordingly until the face is in the middle frame.

Visuals from the robot are not stored anywhere and the data from both the visual as well as the thermal camera is only used for its purpose and then discarded. A figure of how the robot sees both from its visual and thermal camera is seen in figure 5.15.

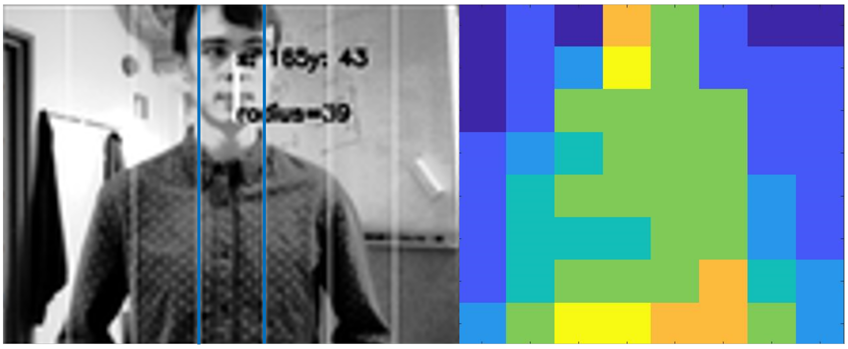


Figure 5.15. *A side-by-side comparison of how the robot sees a person in front of it. Photos by authors.*

5.3.5 Finite-state Machine

A A finite-state machine (FSM) is a mathematical model used to create and evaluate discrete-behavior algorithms and systems. It is made up of a finite collection of states, transitions in those states, and actions that are done during those changes. The behavior of computer programs, communication protocols, and other systems that can be described as a collection of discrete states and transitions is frequently designed and analyzed using FSMs. An FSM could be used to model and regulate the emotional behavior of an emotionally expressive robot. For instance, the robot might have a state for every emotion it expresses (such as happiness, sadness, anger, etc.), and transitions between those states could be triggered by external events or stimuli. Changes in the robot's face expression, posture, or vocalizations may be made when it switches between states. In this robot a simplified version of this was implemented. All emotions were generalised into the "Playing emotion" state. Other states included: Closed, Awake (idle). This provided a framework for the FSM however its functionality was too limited to be used during the demo.

Chapter 6

Validation

Once all the mechanical parts were done and the software was implemented, it was time to do some validation tests.

6.1 Validation Survey

To investigate the expressiveness capability of the robot a web-based questionnaire was made as stated in the methodology chapter. A web-based questionnaire is ideal to quickly reach a focus group without a lot of resources. Together with the stakeholder it was decided to send the questionnaire to the students from the Mechatronics master as well as family and friends of the team members. Following the recommendations by Saunders et al. [88] it was decided to include both open questions (guess the emotion) and category questions (choose from a list of emotions). The questionnaire was divided into two parts, the first part contains six videos, one for each emotion that the robot is able to express. Together with each video an open-ended question was made, where the participant is asked to write the emotion they associate with the video. The second part contained the same videos, and the same questions were asked, but this time it was closed-end questions and the participant had to choose from a list of emotions, where they were only able to choose one emotion. The videos of the emotions are in a random order in both the first part and the second. To verify weather colors and graphic enhance the expressiveness of the robot, it was decided to create two questionnaires, one with colors and graphics and one without. There were no time limits to either the video nor the questions so the participants could watch the sequence as many times as they like. They could also navigate back and forth between the questions. Apart from this, the participants were also asked about their ages and what country they are from. The two questionnaires can be viewed in appendix H. Finally, the results of the questionnaire were analyzed statistically. Similar to Santos et al. [89] the hypothesis that participants will perform better than chance in identifying the six basic emotions in each video was tested.

6.2 Reliability Testing

To test long-term reliability, a loop was created in which the robot would wake up from the closed state, perform several motions, utilize all motors as well as the eye displays and the LED, and then close itself again. This motion loop was then run non-stop for several hours to test the robot's performance. Each iteration loop took 40.75 seconds to complete and after each loop, the temperature was recorded from all smart motors. In addition, a thermal camera image of the robot was manually taken every 20 minutes (due to camera availability photos were only taken during the first test run). The test was performed with the back half of the shell not mounted, for a motivation see paragraph two in section 6.4 below.

Due to inconclusive temperature logs, a total of three test runs were performed. While the first run was long enough to test the reliability requirement of four hours, the goal for the later tests was to get a result showing all motor temperatures stabilizing at some steady state, something that was not clearly shown with the first test run. The first test ran for approximately 4.5 hours and started after doing some motions already, so the motors did not necessarily start at room temperature. The test run ran for only 26 minutes due to a motor error. It was a "cold start" with the motors resting overnight before the test. So all components can be assumed to start at room temperature. After the second run, all motors were shut down and allowed time to cool down to roughly the same temperature they had before the second test run before doing run number three. Run three was 1.6 hours long and was ended manually when the motor temperatures were assessed as stable. No issues were encountered during this run.

6.3 Noise Level Testing

To ensure a safe noise level from the robot, two tests were performed. The first test was performed during the running of the six basic emotions. The second test was performed during the display of the robot's full range of motions. Both tests were set up in the same way, the robot was placed 1 m from the measuring device on top of a table. The device was also placed on the same table, the microphone facing directly towards the robot. The noise levels were measured using the app *Decibel: dB Sound Level Meter* on an Iphone SE 2020 [90].

Due to logistics, the robot was left with one side open while running. The side left off was made to face the microphone of the measuring device. The tests were then carried out. The motion sequence and measuring of noise were simultaneously started and ended. Both minimum and maximum as well as equivalent sound levels were measured in dB(A). Notes were taken during the test on what motion(s) caused the largest noise spikes. The tests were only carried out once.

Chapter 7

Result

The following chapter will present the results of the tests made to validate the developed robot. The six basic emotions will also be showcased in this chapter.

7.1 The Six Basic Emotions

The final configuration of the six basic emotions can be viewed in figure 7.1. As can be seen in the same figure, some of the final colours of the LED ring do not correspond to the State-of-the-Art findings in table A.3 found in Appendix A. The grey of fear was changed due to the problematic nature of displaying grey light, instead a purple colour was chosen. As a result of this, blue was chosen for sadness instead of purple. Finally, disgust was changed from brown to green to create a greater distinction between this emotion and the three other emotions already in the red-orange-yellow hue family.

Sounds were planned to be implemented into the final design to give the robot more dimension and expressiveness. However, a recurring disconnecting error of the Arduino Nano prevented this. No vibrations were implemented in the design due to the uncertain results presented in the State-of-the-Art. Body language, facial expressions and graphics were modeled after the findings in the State-of-the-Art.

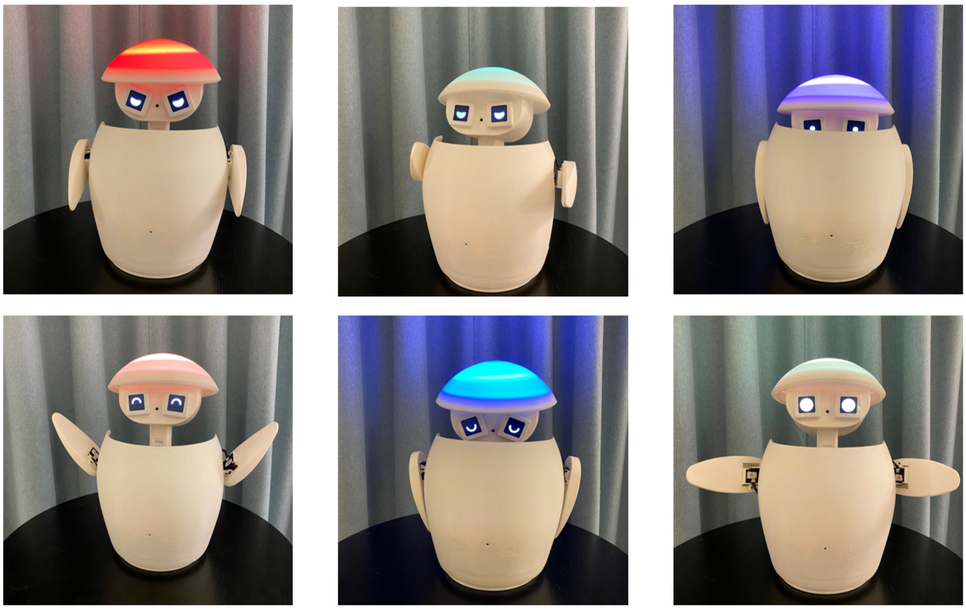


Figure 7.1. The robot displaying all of the emotions. From the top left corner, they are: Anger, Disgust, Fear, Happiness, Sadness and Surprise.

7.2 Expression Capability

From the questionnaire, the following results were derived. In total 73 people answered the questionnaires, 52 people answered the survey containing graphics and colour and 21 answered the one without. These questionnaires were distributed at random. A thing worth stating is that the answers to the open-ended questions have been ignored since they were too widespread in the spectrum of emotions. Also, there has been a typo in the questionnaires, instead of shy it should be fear. Below, are the survey containing graphics and colour referred to as questionnaire 1 and the survey without graphics and colour referred to as questionnaire 2. Apart from the answers given in conjunction with the videos, the participants were also asked about their age, which country they are from and if they had seen the final presentation, where the emotions were already stated.

7.2.1 Questionnaire 1

The following charts in figure 7.2 present what emotion out of the six basic emotions the participants associated with a given video. Each pie-chart represents one video.

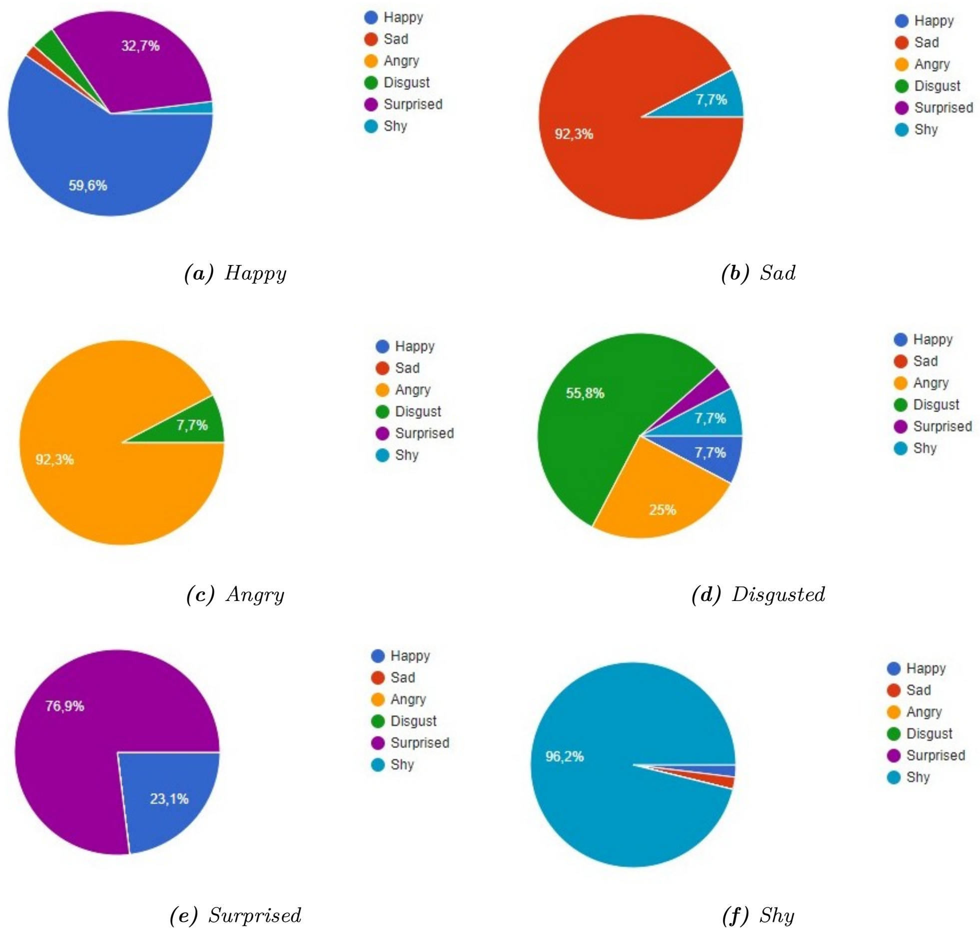
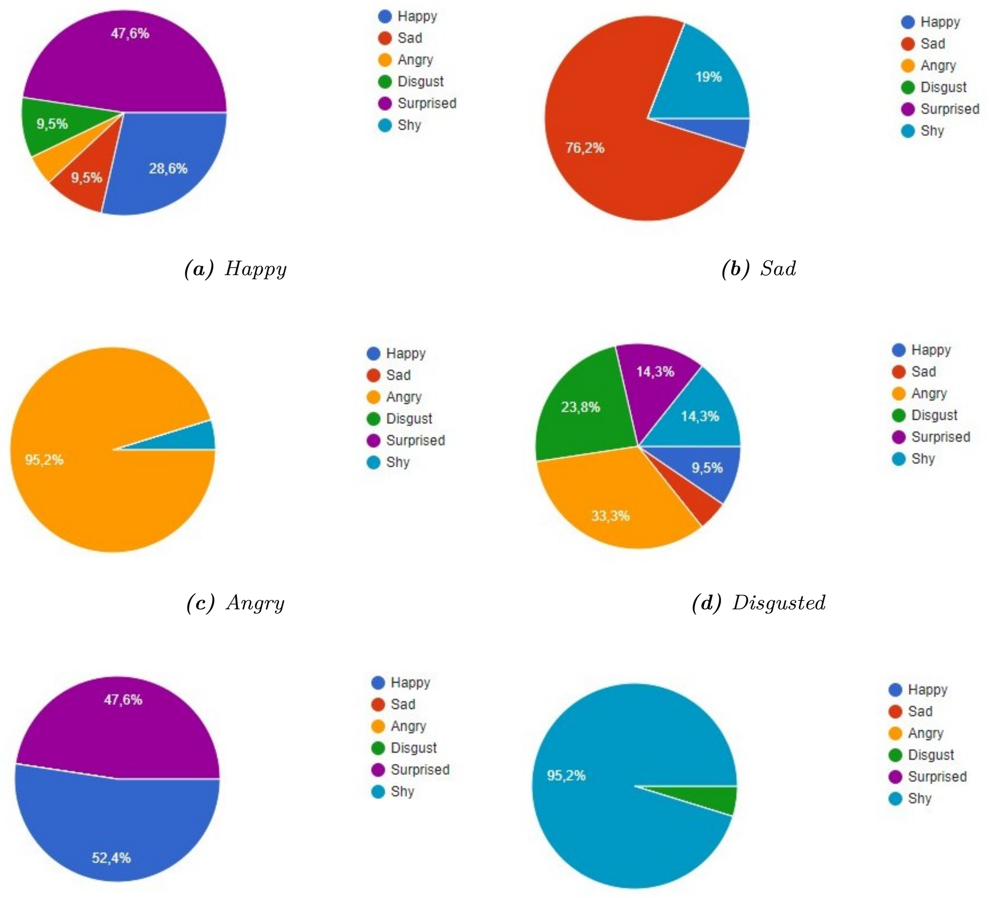


Figure 7.2. *Pie-charts showing which emotion the survey participants associated with the different videos in questionnaire 1. Pie-charts made in Excel.*

7.2.2 Questionnaire 2

As before the following figure 7.3 presents which emotion out of the six basic emotions the participants associated with the given video. The difference in these videos is that there were no eye graphics or colour active in the robot. The expression capability surveyed is therefore only from body language and facial expressions from the rotating eyes.



(a) Happy *(b) Sad*

(c) Angry *(d) Disgusted*

(e) Surprised *(f) Shy*

Figure 7.3. *Pie-charts showing which emotion the survey participants associated with the different videos in questionnaire 2. Pie-charts made in Excel.*

7.2.3 Summary

Table 7.1. *Result from questionnaire 1*

Responses[%]	Happy	Sad	Angry	Disgust	Surprised	Shy
Happy	59,6	0	0	7,7	23,1	1,9
Sad	1,9	92,3	0	0	0	1,9
Angry	0	0	92,3	25	0	0
Disgust	3,8	0	7,7	55,8	0	0
Surprised	32,7	0	0	3,8	76,9	0
Shy	1,9	7,7	0	7,7	0	96,2

Table 7.2. Result from questionnaire 2

Responses[%]	Happy	Sad	Angry	Disgust	Surprised	Shy
Happy	28,6	4,8	0	9,5	52,4	0
Sad	9,5	76,2	0	4,8	0	0
Angry	4,8	0	95,2	33,3	0	0
Disgust	9,5	0	0	23,8	0	4,8
Surprised	47,6	0	0	14,3	47,6	0
Shy	0	19	4,8	14,3	0	95,2

From the results in tables 7.1 and 7.2, it can be seen that the questionnaire with colors and graphics has more accurate answers. In questionnaire 2, it can be seen that angry, sad and shy still have high values but for happy, surprised and disgust the participants did not manage to identify the right emotion. The questionnaire also included questions asking the participant about their age, which country they come from, and if they had seen the final presentation where the emotions are stated, these were not taken into consideration and can be seen in appendix H.

7.3 Reliability Testing

Presented here are the results from the reliability testing. The tests are presented run-wise, with temperature graphs for the Dynamixel motors logged during the test as well as thermal images if any were taken. Also noted are any significant events that occurred during testing.

7.3.1 Run 1

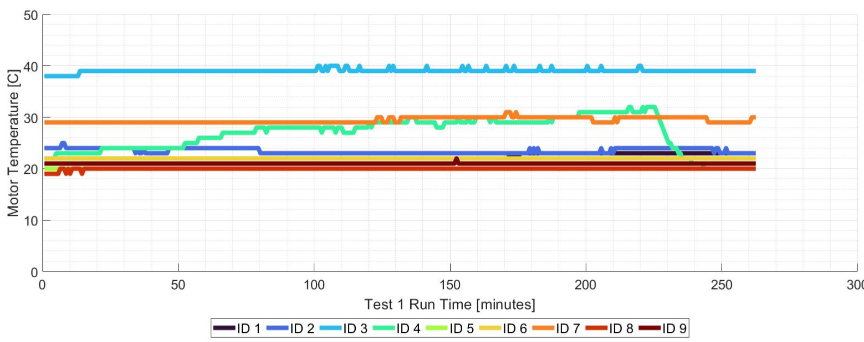


Figure 7.4. Graph of motor temperatures from run 1. Graph made in MATLAB.

Run one (see figure 7.4) was not a cold start so the motor temperatures did not start at room temperature. Component-wise, one failure occurred during the test. Approximately 3.7 hours into the test, motor four stopped working due to an overload error (extension of the right arm). The test was continued regardless with the other motors running as intended. This failure can be clearly seen on the temperature graph as the temperature of motor four decreases rapidly after it stopped. During the test, there was squeaking coming from the slider driven by motor four and the base rotation when rotating the body.

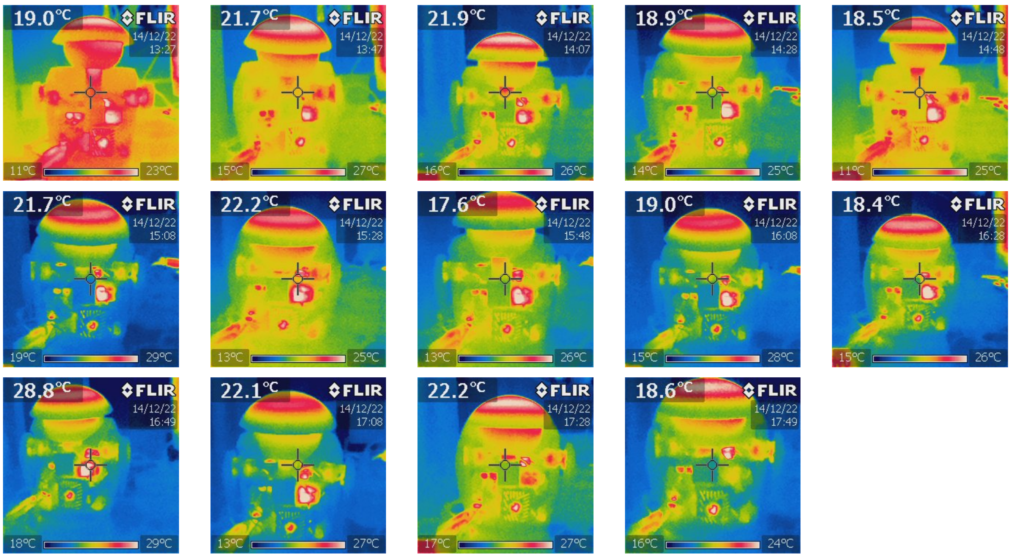
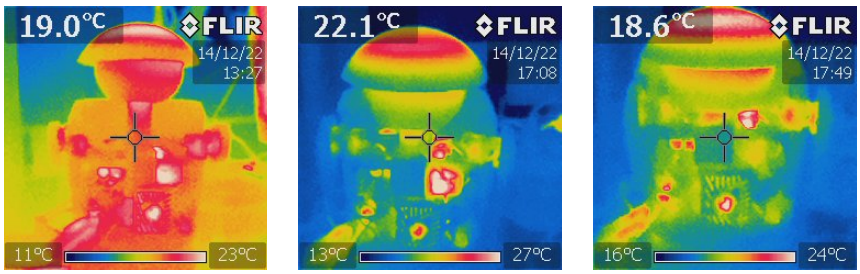


Figure 7.5. *The fourteen thermal images taken during reliability test run 1. Time reads from left to right, one row at a time.*



(a) Start of test run. *(b) Shortly before motor four failure.* *(c) End of test run.*

Figure 7.6. *The first and last thermal images in larger format.*

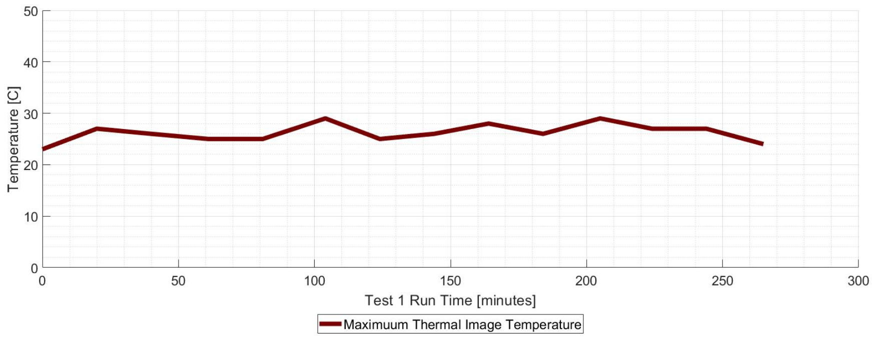


Figure 7.7. *Graph of thermal camera image maximum temperature from run 1. Graph made in MATLAB.*

From figures 7.5-7.7 above from the thermal camera, some of the hottest components visible in the pictures are motor three (the neck lifting motor) as well as motor four that failed, both located to the right of the neck. No component is however distressingly hot on the images and no component is hot enough to harm a user if they were to be touched. Please note that motor four has cooled down on the last picture due to it failing, in accordance with the temperature log.

7.3.2 Run 2

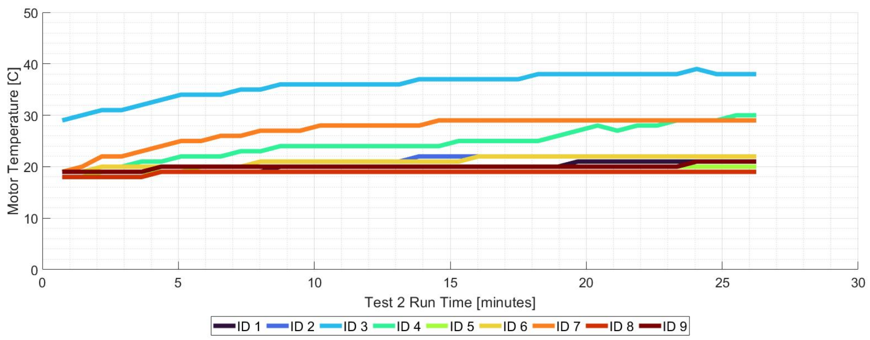


Figure 7.8. *Graph of motor temperatures from run 2. Graph made in MATLAB.*

Run two (see figure 7.8) was a cold start with the robot resting in a room temperature environment overnight before the test and the motors were not powered in any way before the test started. It is therefore noteworthy that motor three does not start at room temperature and instead starts at 29 degrees Celsius. This test was performed to get a clearer view of the motor heating and steady-state compared to run one but was cut short by motor four once again throwing an overload error and turning off. Because of this test three was performed after the motors had cooled to roughly the same temperatures as at the beginning of run two. Similar to run one there was squeaking from the base rotation and the slider driven by motor four during test run two.

7.3.3 Run 3

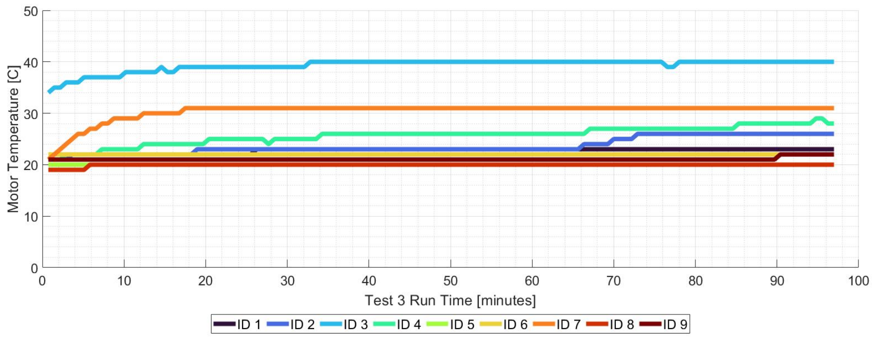


Figure 7.9. *Graph of motor temperatures from run 3. Graph made in MATLAB.*

Run three (see figure 7.9) was as stated above performed after run two, with some time for the motors to cool in between. Due to time constraints, motor three was not given enough time to cool to the same level as the start of run two (room temperature) but the other motors started from approximately the same temperature as the cold start. Run three was performed without issues except for squeaking. Noteworthy is that the squeaking intensity seemed to increase at roughly 65 minutes, at the same time as motor four (arm slider) and two (base rotation) both increased in temperature. The test run ended when available time ran out, but with all motor temperatures except motors two and four having reached a steady state.

7.3.4 Summary

Overall, no component reached temperatures worthy of concern during any of the tests. The hottest motor according to the log was motor 3 (neck lifting) which reached 40 degrees Celsius. It not starting at room temperature during run two is however an anomaly. Also concerning are the two failures of motor four during test runs one and two as well as the squeaking of joints four and two. Potential causes and solutions are covered in the discussion.

7.4 Noise Testing

Presented below are the results from the two noise level tests.

7.4.1 The Six Basic Emotions Noise Test

The first test that was performed by letting the six basic emotions run one after another. The test ran for 53 sec. In figure 7.10, a graph of the noise test stating the relationship between sound pressure levels and frequency can be seen.

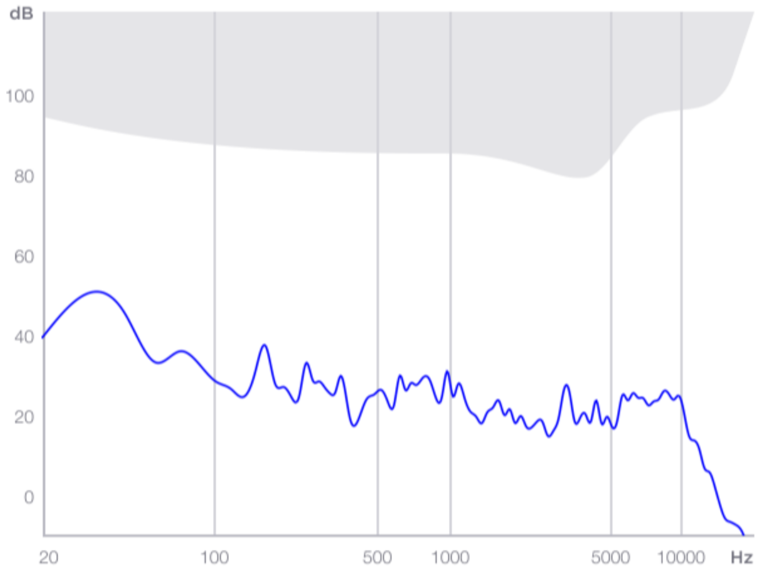


Figure 7.10. *Graph of sound pressure levels as a function of frequency for the six basic emotions noise test.*

The minimum sound level was 37 dBA, the maximum 57 dBA and the equivalent sound level, LAeq, was 45 dBA, as can be seen in table 7.3.

Table 7.3. *Sound pressure levels, dB, in octave frequency bands with geometric mean frequencies, Hz, for the six basic emotions*

	63	**125**	**250**	**500**	**1000**	**2000**	**4000**	**8000**	**Equivalent sound levels, dBA**
LAeq	49	47	45	37	31	29	22	26	45
Maximum	55	52	53	46	51	45	40	41	57
Minimum	44	40	37	27	24	21	15	17	37

7.4.2 Full Range of Motions Noise Test

The second test was performed by letting the robot show its full range of motion of all its components. This test lasted for 1 min and 34 sec. Down below a graph of the test can be viewed, see figure 7.11.

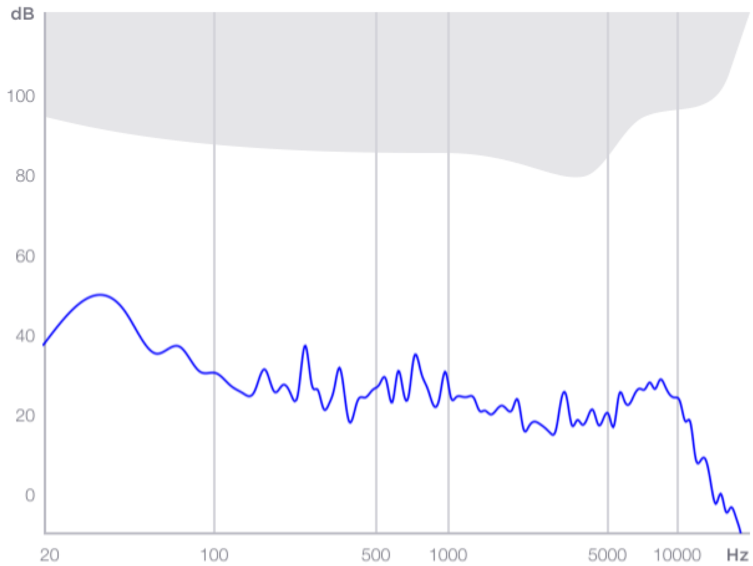


Figure 7.11. Graph of sound pressure levels as a function of frequency for the full range of motions noise test.

The minimum sound level was 38 dBA, the maximum 56 dBA and the equivalent sound level, LAeq, was 46 dBA, see table 7.4

Table 7.4. Sound pressure levels, dB, in octave frequency bands with geometric mean frequencies, Hz, for the full range of motions noise test.

	63	125	250	500	1000	2000	4000	8000	Equivalent sound levels, dBA
LAeq	49	47	41	35	35	28	22	28	48
Maximum	53	52	47	48	55	40	37	44	56
Minimum	44	38	33	27	24	20	15	17	38

7.5 Requirements

To fully evaluate the final design of the robot, a run through of all requirements given in section 1.3 is needed. Down below, two lists will be provided, with the motivations to whether or not the must-have-requirements and the nice-to-have-requirements were fulfilled.

Must-have-requirements

1. **The robot should comply with requirements 3 and 6 from UNICEFs policy guidelines on AI for children.**

a) **Prioritize fairness and non-discrimination for children.**

b) **Provide transparency, explainability, and accountability for children.**

The robot complies with requirements 3 and 6 from UNICEFs policy guidelines on AI for children. Firstly, the robot prioritizes fairness and non-discrimination for children. When implementing colours, the association between them and emotions were looked at from a cultural perspective, choosing the most common emotion-colour association for each of the six basic emotions. Thus, giving every child an equal chance to understand the robot, no matter cultural background.

Secondly, the robot provides transparency through the placement of its camera and the overall design, i.e. once the robot is closed, it has no chance to record you as the camera is inside. Accountability is provided through the use of smart motors with current sensing. The camera placement and the robot's design also adds to the accountability. Explainability could not be implemented in the current version of the robot, see the section 9.4 for more details.

2. **The robot should be understandable by people of all ages, but specifically designed for children between the ages of 5 to 16.**

   The robot is, with the inclusion of colours and graphics, understandable to adults. However, very little can be said about children's understanding of the robot.

3. **The robot should be able to express emotions through body movement and/or facial features.**

   The robot can express emotions through body movement and facial features.

4. **The robot should be able to express the 6 basic emotions of: happiness, sadness, anger, fear, surprise, and disgust.**

   The robot can express the six basic emotions, however to a varying degree as presented above.

5. **The robot should provide safe interaction with its user, this in terms of both physical and psychological safety.**

   The implementation of motors with current sensors, as well as the main component material being plastic, the robot can be said to provide a safe physical interaction. Likewise, psychological safety is achieved by providing fairness and non-discrimination as well as transparency, explainability and accountability. The capability of expression negative emotions should be used carefully.

6. **The robot should be reliable and be able to run for several hours without issues requiring service.**

   If it were not for the reoccurring overload error of motor four, there seems to be no other reason preventing the robot from running for several hours (as seen in Run 1). More on this in the Discussion, chapter 8.

7. **The robot should have multiple Degrees-of-Freedom. Motors and sensors should enable required localization and perception.**

   The robot has 11 Degrees-of-Freedom. The choice of motors and sensors enables the required localization and perception.

8. **In addition to the hardware design Motion control, planning algorithms and software for enabling reliable and safe operation should be developed.**

   Hardware design, motion control, planning algorithms and software have been developed for reliable and safe operation as described above.

Nice-to-have-requirements

1. **The robot should be able to track a person in its surroundings.** The robot can, due to the implementation of OpenCV, track and localize a person in its surroundings.

2. **The robot should be able to greet the user upon first interaction.** The robot can greet the user upon first interaction as soon as OpenCV has identified said user.

3. **The robot should be able to express itself using additional nonverbal channels such as sound, colour, haptics and/or graphics.** The robot can express itself, besides the use of body language and facial expressions, through the means of colour and graphics. Sound (and speakers) has been implemented in the design of the robot but not in its emotional expressions. Haptics and vibrations have not been implemented.

4. **The robot should not produce noise levels above 45dB from a distance of one meter.** The robot produces a maximum noise level above 45dB. Hence the requirement has not been met.

5. **The dimension of the robot should be in the interval: height: 10-40 cm, base: 5-30 cm.** In its closed state, the robot has a height of 28 cm. The base diameter is 20 cm.

Chapter 8

Discussion

The results indicate a successful implementation, as the majority of the requirements have been met. The overall cost of all components is 918€ (see appendix F.1 for a detailed price list). At the beginning of the second phase of the project three cost options were presented to the stakeholder. The final cost lies between the compromise and quality cost option which is an acceptable result. However, the robot was only a prototype and all mechatronic areas were developed almost simultaneously. The validation and testing process was done as a last step of the project, without leaving any time space for potential improvements. In the meantime, the team has come up with problems and solutions that will be discussed in the upcoming sections.

8.1 Noise Level

One of the most undesirable results was the noise level generated by the robot during a run, regardless of which pre-programmed trajectory path that was used. According to our stakeholder, a desirable maximum sound level for the robot should be 45 dB. Figure 7.10 and Figure 7.11 corresponding to the values in Table 7.3 and Table 7.4 show that the equivalent constant sound level by running the emotions meets the requirement and that the run of the full motion range generates slightly higher sound level. However, the peak of the generated sound is too high in both cases and therefore potential solutions to solve this problem are provided in the next section.

Three critical sources have been identified, which may cause higher noise levels compared to other parts of the robot. These are the rack and pinion mechanism in the arms,the base and the motors themselves, especially the XL430 servo lifting the neck. The main reason for the higher sound level, in the arms and the base, is squeaking caused by friction between the plastic parts. Since the parts have been 3D printed, their surface can remain rough, even after a sanding process. As shown in Figure 5.4 the robot rests on a base consisting of a gear mechanism. In the middle of the base, a bearing was added in order to enable a smoother motion but the uneven weight distribution can cause squeaking in the outer part of the base due to friction and bad tolerances.

8.2 Survey Results

From the validation 6.1 it is mentioned we wanted to test the hypothesis that participants will perform better than chance in identifying the six basic emotions in each video. To investigate this, two questionnaires were made. As mentioned in the results, we can see from table 7.1 that the questionnaire with colors and eye graphics has more accurate answers compared to the one without 7.2. The participants did perform better than chance in identifying all of the six basic emotions in questionnaire 1. However, in questionnaire 2, the participant did not perform better than chance in identifying the emotions happy, surprised and disgust, see table 7.2. Since there was a typo in the questionnaire, where shy should be fear, we can not evaluate this outcome because shy is not one of the six basic emotions. Another conclusion that can be drawn from table 7.1 and 7.2 is that color and eye graphics can help enhance some emotions, like happy, sad, disgust and surprised, but for some like anger it does not. The questionnaires also include questions asking the participants about age, country and if they had seen the final presentation, were the emotions where stated. As we have not taken these question in consideration or evaluated them, they will be not discussed further.

8.3 Reliability

As is, the robot cannot be considered reliable, the culprit being the two failures experienced by motor four during testing. To examine the fault, it is interesting to compare motor four with motor seven. The two motors are driving what should be two of the same mechanisms, but only the mechanism for motor four is squeaking and only motor four failed during testing. From the squeaking it would not be unreasonable to consider that the motor faults are caused by intermittent friction in the prismatic joint. Assuming that motor four experiences increased friction and higher loads compared to motor seven would explain the higher steady state temperature seen in test runs one and two (figures 7.4,7.4). Those runs were however the test runs where motor four threw and overload error so the loading might well have been higher during those runs in comparison to test run three, meaning friction in the joint might be inconsistent. On the topic of inconsistent friction it is also worth mentioning the observation from test run three, that the motor temperatures of two and four seemed to increase at the same time as the squeaking intensity increased, adding weight to the hypothesis that the causes of the motor faults and squeaking are related.

With available data it is impossible to narrow down on an exact cause but an informed guess can be made. Taking everything from the last paragraph into account it would seem that the mechanisms for motor two and four (but especially four) have problems with intermittent rubbing between some parts. This increases friction and motor load and is likely the cause of the squeaking and also what is causing motor four to fail while motor seven runs without issue. Inconsistent motor loads could also explain why the heating curve for motor four is not a clear exponential curve as we would expect if the heat generated was somewhat constant (again, compare to motor seven). To possibly resolve the issue there are several things to test. The simplest is to start with lubrication of the joints. Currently the joints are run dry and lubrication has a chance to resolve the issues. A further step if the overloading errors remain after lubrication could be to swap places of motor four and seven. If the issue of overloading moves with motor four, the the problem stems from the motor itself, if motor seven overloads instead, the issue is located somewhere in the slider mechanism. If the slider mechanism is determined as the cause, all parts should be inspected for damage or wear and to resolve the issue parts might have to be reprinted or redesigned. Exactly what needs to be changed cannot be stated with current information but the design of the sliders should be examined and aimed to be improved even if a simple lubrication resolves the current issues. This should be done as the experienced faults are signaling some manner of design or manufacturing error that could reappear, even if a lubrication resolves it in the short term.

On another note, it is also worth discussing the temperatures measured. As stated in the results section, none of the temperatures measured during testing are worthy of concern and should not cause damage to any component. There is however the fact that the temperatures were measured while half the shell was not mounted. This was done in order to facilitate photography of the internals with the thermal camera, but could very well result in an advantageous cooling solution. To really be viable, the temperature measurements should be redone with the shell fully closed as there is a possibility that the available intake area on the bottom of the robot is not sufficient and that a closed shell would lead to choked airflow and higher temperatures overall. Separate to that, the irregular temperature of motor three should also be examined. During the cold start of run two it measured 29 degrees Celsius, 10 degrees above the other motors. From the fact that the motor had not been powered for over ten hours and the robot had been stored in room temperature, it is safe to assume that the motor's actual temperature was the same as the other motors, i.e. at room temperature. Judging from the temperature graphs it seems as the motor sensor detects the increasing temperature while running, but that the sensor calibration is off. Either the zero point is wrong, the gain is wrong, or both. As an external source of data we have the images from the thermal camera that show the external temperature of motor three to be roughly the same as motor four during test run 1 (fig. 7.5). If we assume the two motors to have the same temperature based on the thermal camera, the error in the sensor reading is roughly 10 degrees according to the logged data (fig. 7.4). A hypothesis is therefore that the temperature sensor in motor three measures 10 degrees to hot, but further testing is needed to verify or disprove this.

Chapter 9

Future work

Presented below are some suggestions of future work of the project.

9.1 Design and Mechanics

A lot of time has been spent on the design of the robot, and the team tried to include as many wishes from each member as possible in the prototype, from degrees of freedom to appearance. Despite the near professional design, there are a few things that could be improved in a potential further development of the robot. To start with, it is important to look further into the tolerances of the base and the bearing, in order to avoid the squeaking sound caused by the uneven distribution of the weight. Similarly, the tolerances in the rack and pinion of the arms should be double checked. Here, the simplest solution is to use silver tape between the surfaces in combination with lubrication (possibly Lithium Grease or a PTFE based lubricant). Alternatively, a solution could be to print these in another material or modify the design to put metallic parts between the contact surface. In addition, it is important to examine how the UP Core will be controlled wireless, in order to determine if the hole in the middle of the base will be wider to fit HDMI, and USB cables for a screen, keyboard and mouse. In the current setup, using both parts of the shell only allows wireless control of the UP Core's terminal through TeamViewer. Furthermore, the possibility of repositioning the speakers and moving the thermal camera to the head without compromising the appearance may also be investigated. Finally, it is of high interest to investigate the possibility of 3D printing the robot parts with materials such as ABS which would provide smoother surfaces as well as the possibility of using soft parts in the robot.

The assembly of the robot could be further developed. Right now it is quite hard to disassemble the robot once all the parts are screwed in place as well as when all the electronics are plugged in. A few iterations of this assembly-minded CAD model have already been done during the project and we believe that one more round of figuring out the best way of how all parts fit together the best way will greatly improve the final assembly.

9.2 Electronics

In order to optimize the robot both design-wise and its functionality, some parts of the electronics could be modified. To start with, all cables should be designed in the CAD model, paths should be created so they are not loose inside the robot and their length should be optimized, including the USB cables. In addition, the two cables leading to motor number one, needed to be extended by soldering on new cables. These should be ordered in the correct length (40cm). Furthermore, some problems occurred with the Arduino Nano with periodical disconnections, therefore we believe that it should be replaced with a new one. Finally, the component sharing voltage to each part could also be optimized by minimazing it's size, and the SG90 servos could have been replaced with servo motors that do not cause as much noise.

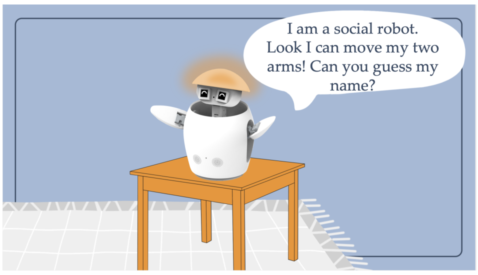
9.3 Motion Control and FSM

The emotions were as mentioned implemented using ”keyframes” that store the goal position for a motor during a specific time. This could be expanded upon to get smoother and less robotic movements. One solution for this would be to use an animation software (For example: Blender,Maya) and then export the keyframes from there. Another implementation could be using a mathematical model for modeling the motions. The FSM is also a subject to be expanded on in the future. This could allow the robot to appear less predictable.

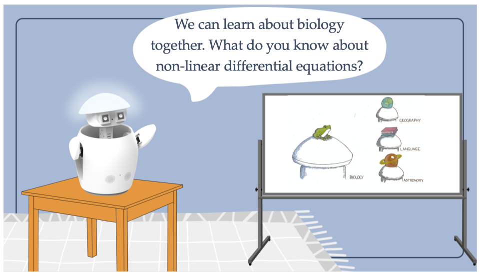
9.4 Explainability and Interaction

As introduced in section 3.1 explainability is a key point from the UNICEF guidelines. Even though the explainabiltiy of the robot so far is limited many necessary components have already been installed to enable explainability. Among others the speakers can be used to give the robot a voice. Comparable to the set-up mode of a new phone the robot could use its voice to explain itself when first started. This could include information about motion, sensing and interaction capabilities. One example can be seen in figure 9.1a In this context it could be useful to implement a text to speech function.

As described in section 5.1.3 the head is designed as two parts. The upper part can be taken of and exchanged. One could use this feature to equip the robot with different hats. One example could be to use the robot as a story telling educator as shown in figure 9.1b. Developing further use cases for the robot is a topic of future research. For this it would be useful to cooperate with other departments.



(a) The robot introducing itself and explaining its motion capabilities.



(b) The robot in a potential use-case. The user can choose between different hats.

Figure 9.1. *A vision for future interaction.*

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Appendix A

Basic Emotion Characteristics

Here we present the tables used to summarize our findings from the different research fields regarding emotional expression. These tables were used as references in the concept design phase to decide on what features and degrees of freedom was most important.

Table A.1. *BODY LANGUAGE*

	Head	**Spine**	**Arms**	**Movement**	**Weight**
HAPPINESS	Looking Up, Forward	Arched Backward, stretched	Raised Up (straight), hanging	High, low movement dynamics	Normal
SADNESS	Looking Down, forward	Arched Forward	Hanging Down, hanging	Low	Normal
ANGER	Looking Forward	Arched Forward, bowing	Close Frontal	High	Forward
SURPRISE	Looking Forward	Straight	Raised Up	High, overall backward movement	Backward
DISGUST	Looking Up/Side	Straight w. Sidetwist	Outstreched Frontal	Low, Arms opposite to head	Backward
FEAR	Looking Forward	Arched Forward	Hanging Down/Frontal, closing	Medium/High	Backward

Table A.2. FACIAL EXPRESSION

	Mouth	**Brows**	**Cheek**	**Eyes**	**Nose**
HAPPINESS	Lip corner puller	Outer and inner brow raiser	Cheek raises	Lid high	
SADNESS	Lip corner depressor	Brows lowers overall but inner brow raises	Check lowers	Lid low	
ANGER	Lip tighten	Brow lower, outer brow raises		Lid tightens	
SURPRISE	Jaw drop and lips apart	Outer and inner brow raises		Big eyes, lid high	
DISGUST	Lip corner depressor and lips apart	Brows lowers		Lid low	Nose wrinkles
FEAR	Lip stretches and apart	Outer and Inner brow raises		Upper lid raises	

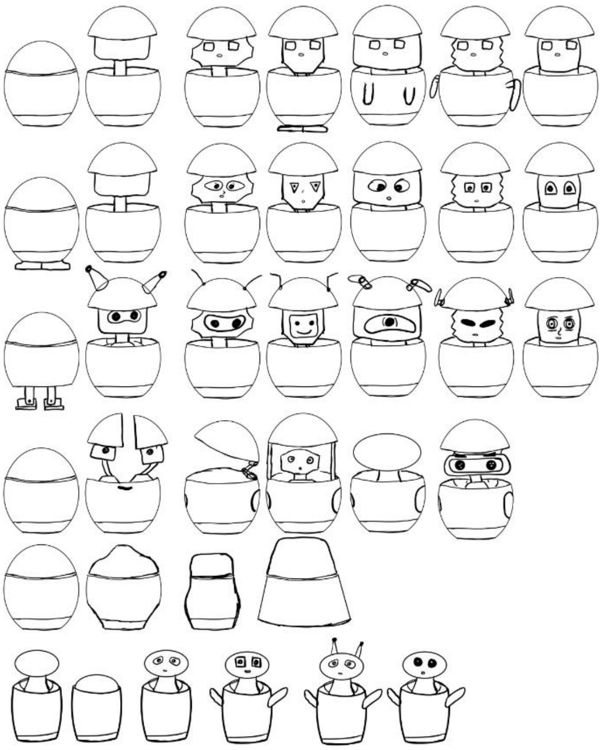
Table A.3. COLOURS, VIBRATIONS AND SOUND

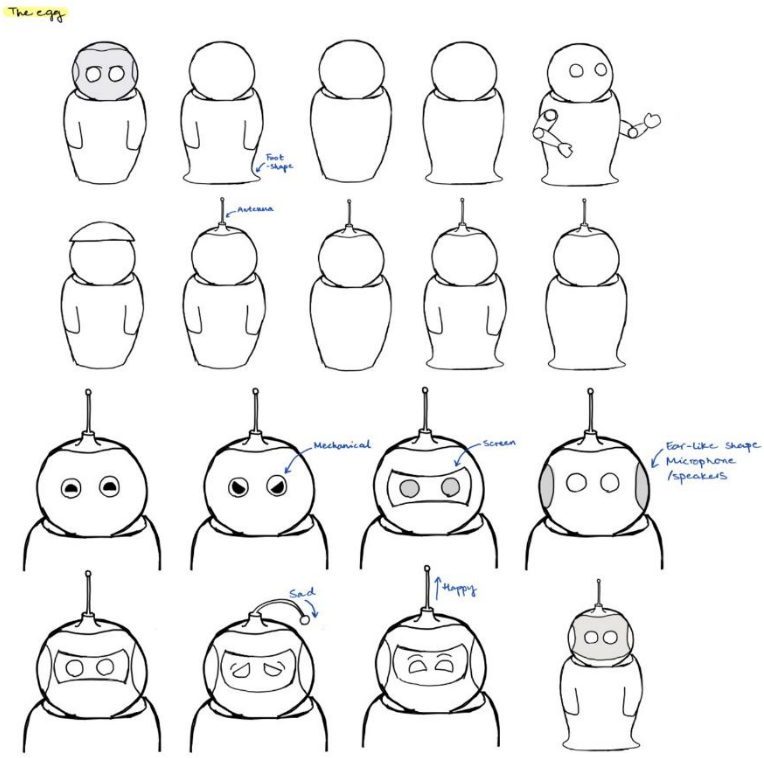
	Colour (HSB)	**Comment**	**Vibrations**	**Sound**
HAPPINESS	45/100/100	Bright orange	Non	
SADNESS	230/40/40	Dull purple		Falling
ANGER	0/100/100	Bright red	Highly intense	Rising
SURPRISE	60/100/100	Bright yellow	Non	
DISGUST	30/67/40	Low brightness	Brown	
FEAR	0/0/20	Grey		

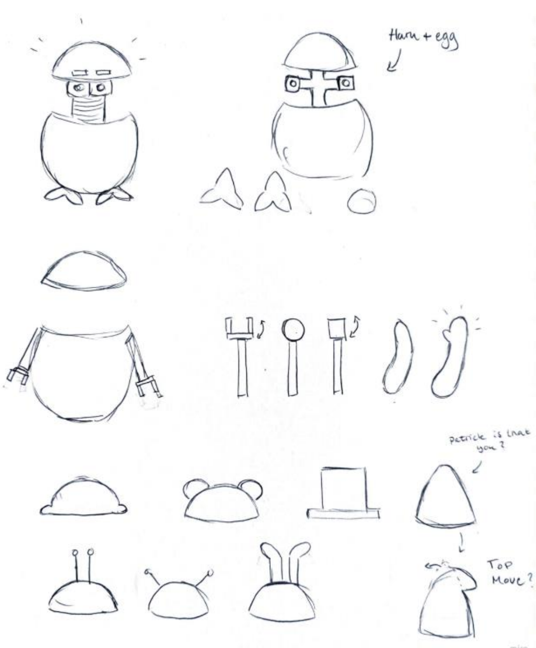
Appendix B

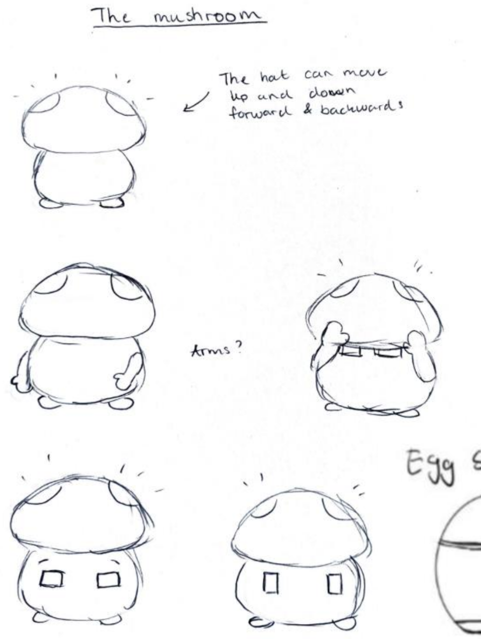
Sketches

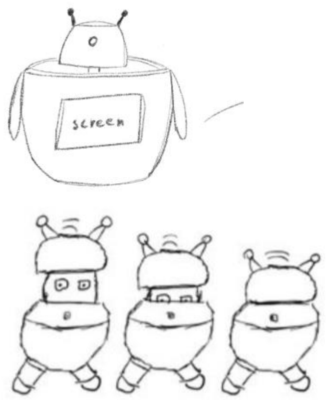
B.1 Egg sketches

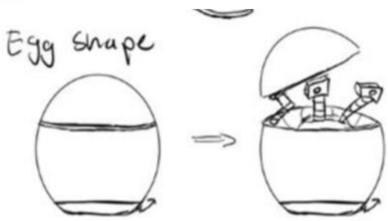


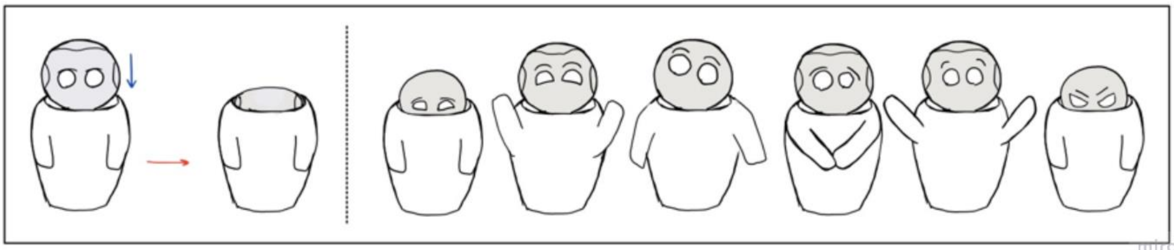

The egg
Foot
-shape
Antenna
Mechanical
Screen
Ear-like shape
Microphone
/speakers
Sad
Happy


Harn + egg
Patrick is that you?
Top
Move?

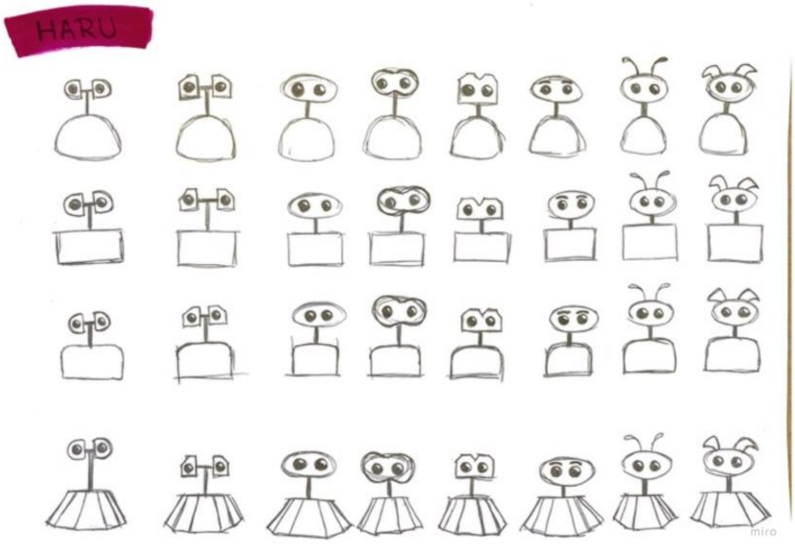

The mushroom
The hat can move
up and down
forward & backwards
Arms?

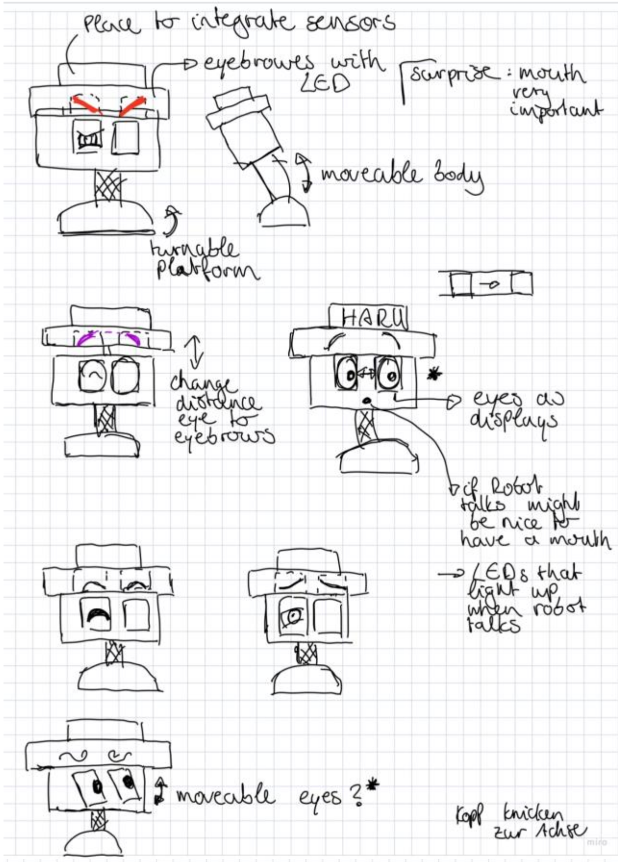

screen

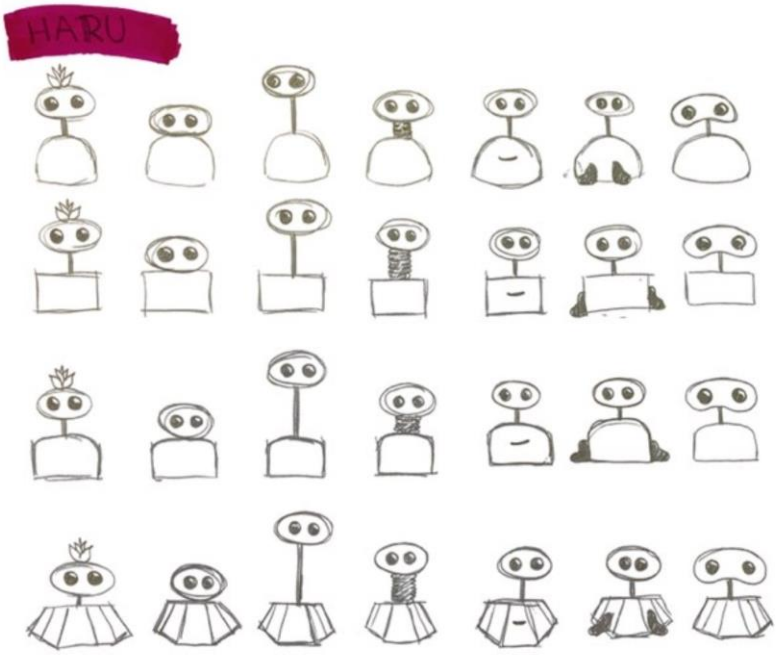

Egg shape

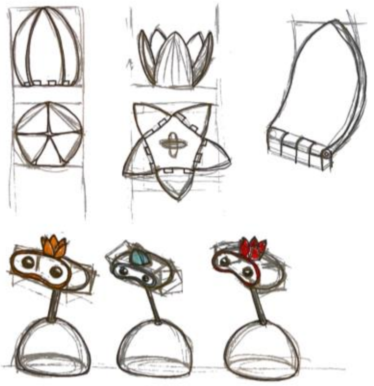


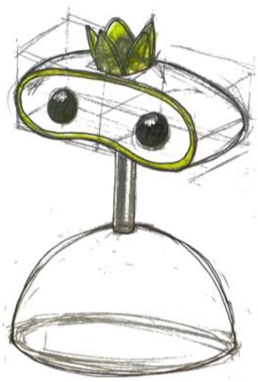
B.2 Haru sketches

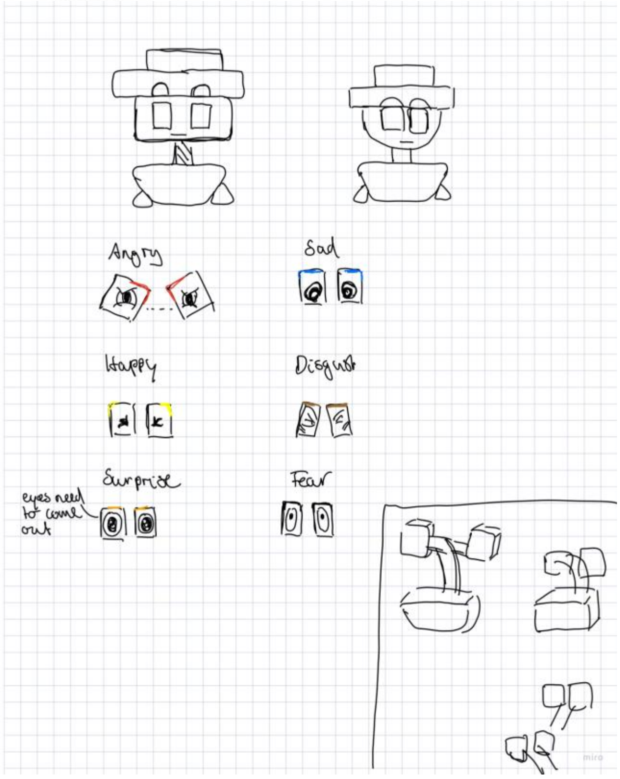

HARU

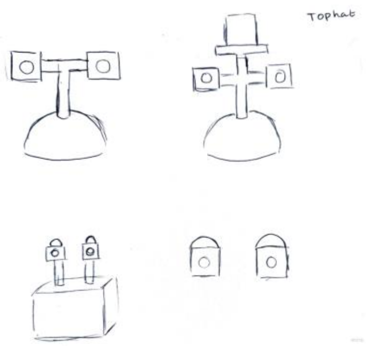

Place to integrate sensors
eyebrowes with LED
surprise: mouth very important
moveable body
turnable platform
change distance eye to eyebrows
HARU
eyes as displays
if Robot talks might be nice to have a mouth
LEDs that light up when robot talks
moveable eyes ?*
Kopf knicken zur Achse

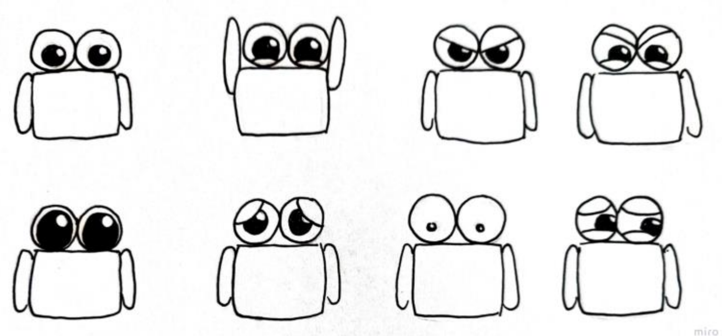

HARU





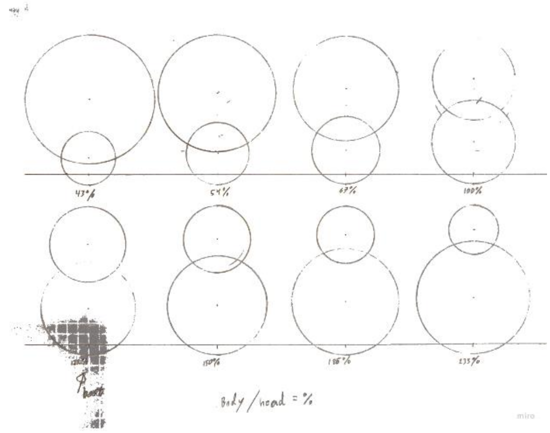

Angry
Sad
Happy
Disgust
Surprise
Fear
eyes need to come out


Tophat

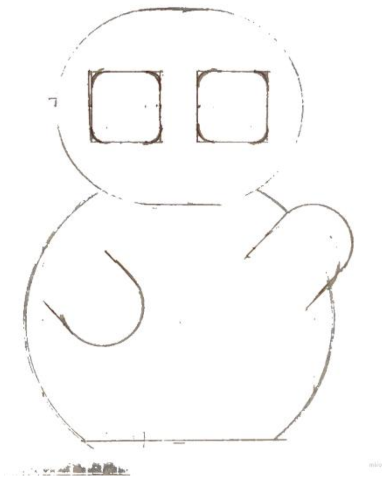


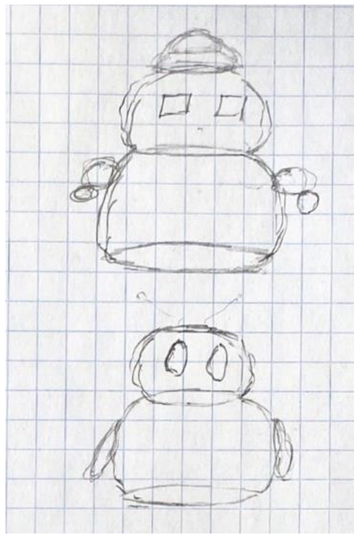
B.3 Snowman sketches

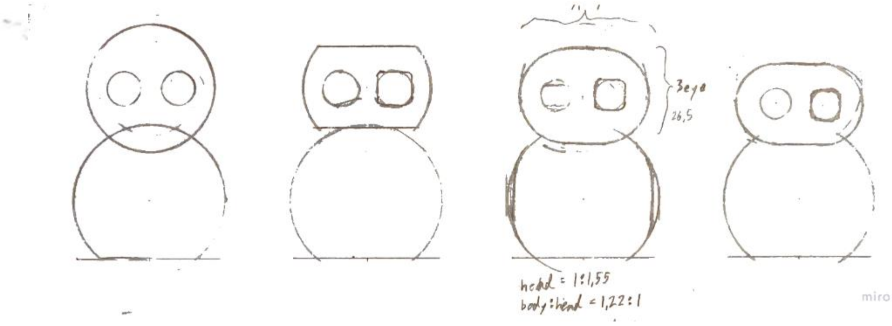

SNOWMAN

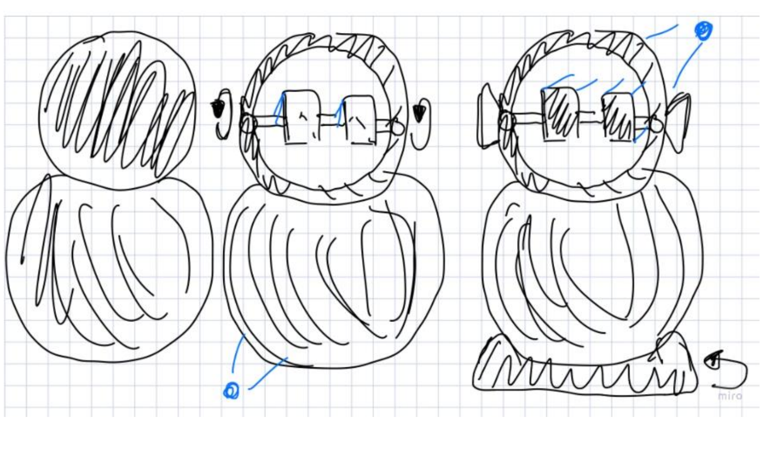

Body / head = %


SNOWMAN
from the back



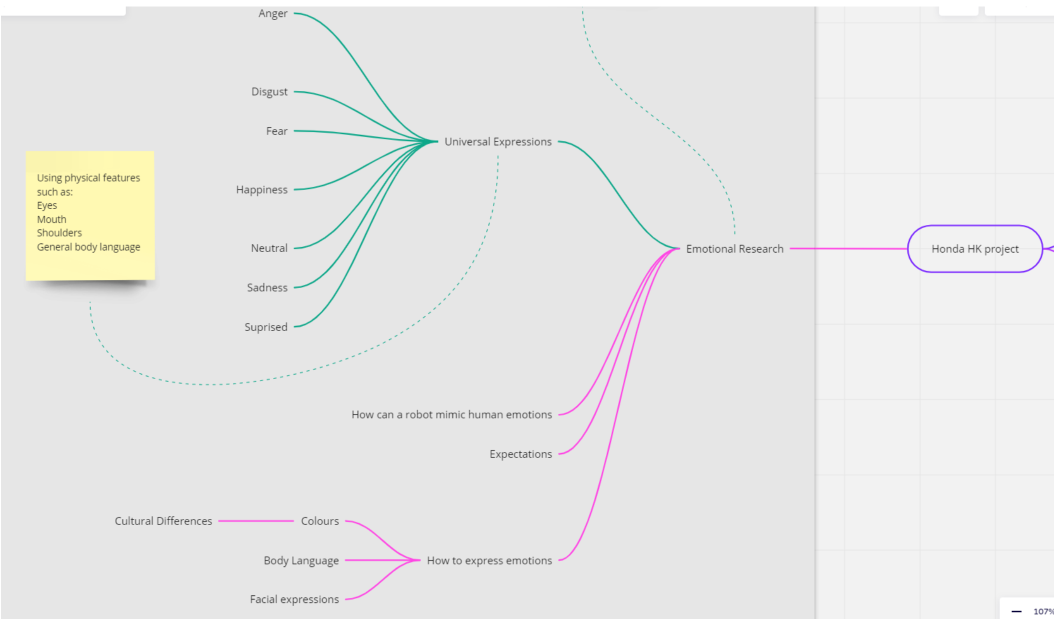


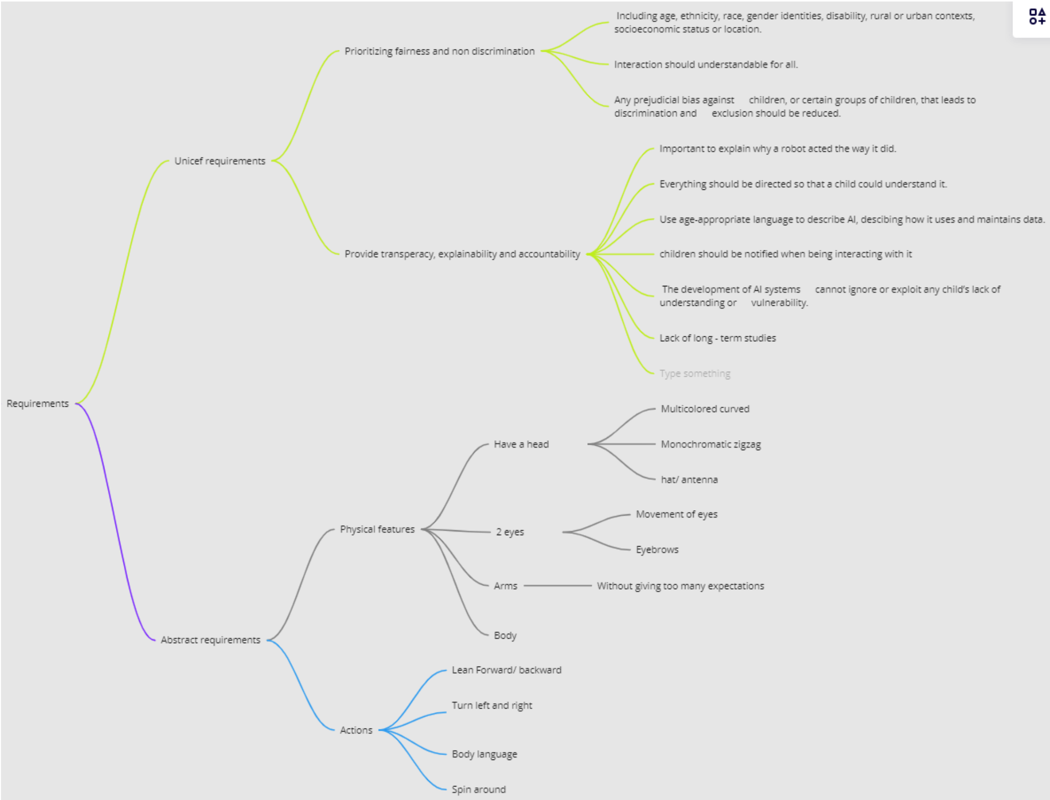

head = 1:1,55
body:head = 1,22:1

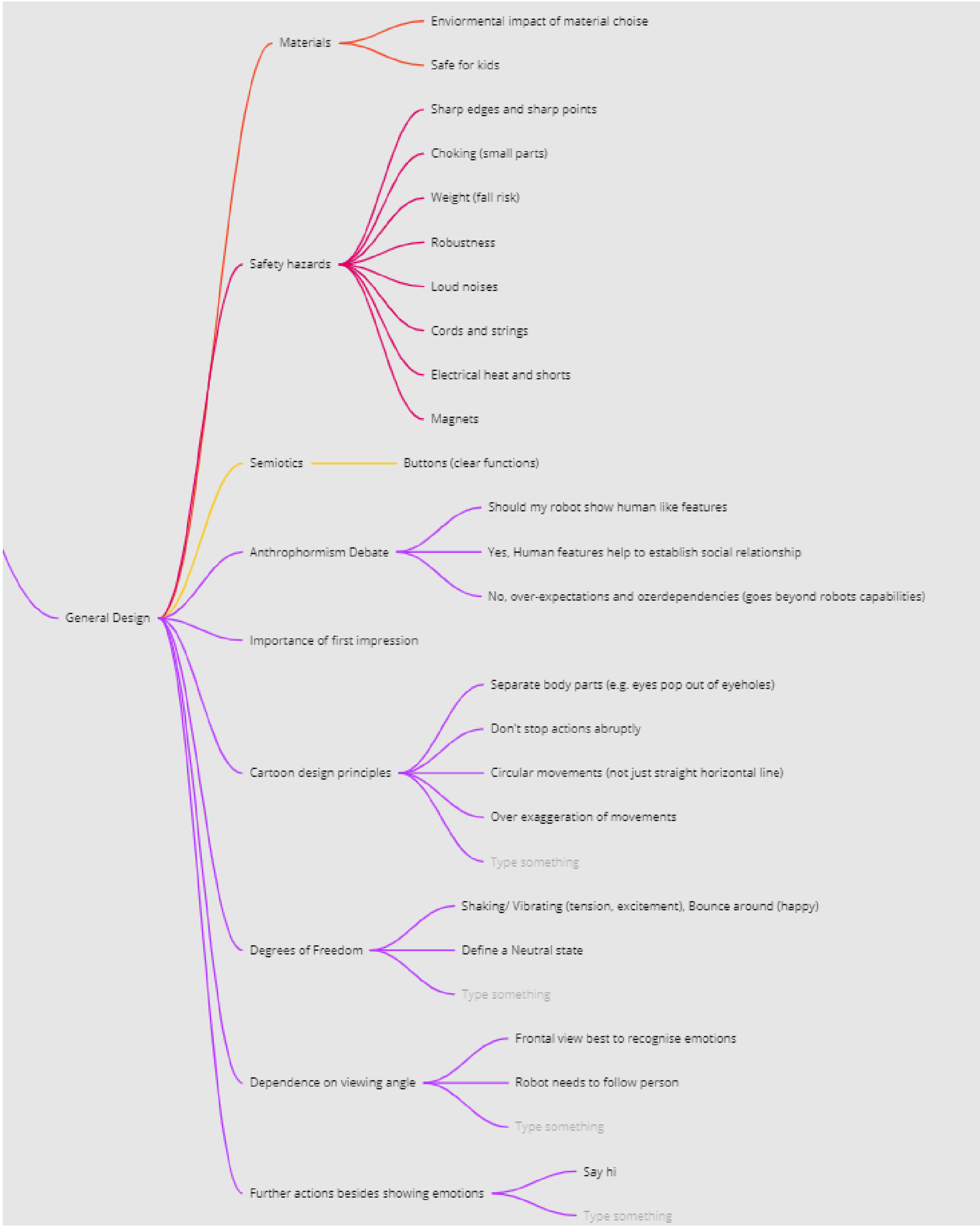


Appendix C

Mindmap

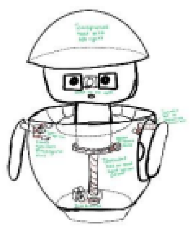



Requirements
Unicef requirements
Prioritizing fairness and non discrimination
Including age, ethnicity, race, gender identities, disability, rural or urban contexts, socioeconomic status or location.
Interaction should understandable for all.
Any prejudicial bias against children, or certain groups of children, that leads to discrimination and exclusion should be reduced.
Provide transperacy, explainability and accountability
Important to explain why a robot acted the way it did.
Everything should be directed so that a child could understand it.
Use age-appropriate language to describe AI, descibing how it uses and maintains data.
children should be notified when being interacting with it
The development of AI systems cannot ignore or exploit any child's lack of understanding or vulnerability.
Lack of long - term studies
Type something
Abstract requirements
Physical features
Have a head
Multicolored curved
Monochromatic zigzag
hat/ antenna
2 eyes
Movement of eyes
Eyebrows
Arms
Without giving too many expectations
Body
Actions
Lean Forward/ backward
Turn left and right
Body language
Spin around


General Design
Materials
Enviormental impact of material choise
Safe for kids
Safety hazards
Sharp edges and sharp points
Choking (small parts)
Weight (fall risk)
Robustness
Loud noises
Cords and strings
Electrical heat and shorts
Magnets
Semiotics
Buttons (clear functions)
Anthrophormism Debate
Should my robot show human like features
Yes, Human features help to establish social relationship
No, over-expectations and ozerdependencies (goes beyond robots capabilities)
Importance of first impression
Cartoon design principles
Separate body parts (e.g. eyes pop out of eyeholes)
Don't stop actions abruptly
Circular movements (not just straight horizontal line)
Over exaggeration of movements
Type something
Degrees of Freedom
Shaking/ Vibrating (tension, excitement), Bounce around (happy)
Define a Neutral state
Type something
Dependence on viewing angle
Frontal view best to recognise emotions
Robot needs to follow person
Type something
Further actions besides showing emotions
Say hi
Type something

Appendix D

Concept Evaluation

Requirements / Robot		
UNICEF		
Prioritize fairness and non-discrimination for children		
transparency, explainability, and accountability for children		
GENERAL		
understandable by people of all ages, designed for children between 5 to 16 years.		
EMOTIONS		
happiness		
sadness		
anger		
fear		
surprise		
disgust		
SAFETY		
physical		
Non physical		
DESIGN / PHYSICAL PRODUCT		
Run time and life expectancy		
Degrees of freedom		
Actuators and sensors enable required localization and perception.		
Hardware, motion control, algorithms and software are reliable and safe		
EXTRA FEATURES		
User and surroundings tracking		
Greeting as a first interaction		
Sound, colors, haptics and graphics		
Result		

Appendix E

Methodology

Figure E.1. *Morphological chart for three sub-systems*

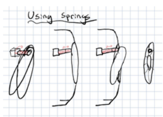
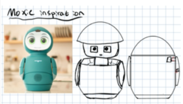
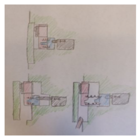
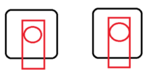
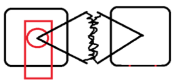
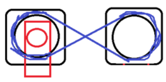
Sub-system	Idea A	B	C	D	E
Arms	**Using a spring:** springloaded telescope pole inside When arm rotates, the friction pushes the arm out 	**Arms outside of the body:** Reducing the complexity of the arms having to come out needs to be flush with the body 	**Rack and pinion:** Easy and simple solution for both rotating and having the arms come out 	**Spring Loaded Parallellogram:** One motor boowden actuates both arms to fold out. One motor per arm to rotate the shoulder 	**Linear actuator:** Small linear actuators that pushes out the arms. Servos rotates the arms. 
Eyes	**Eyes turn independent:** Each Eye has an individual motor. Motor sits directly behind the eyes. 		**Only one motor Turn eyes inverse (Gears)** 	**Only one motor Turn eyes inverse ("Belt")** 	
Neck extension + Neck twist	**Lead screw:** 10cm extension Multi turn servo for screw drive	**Linear actuator:** 10cm extension	**Twist:** +-degrees Thrust bearing /		

Figure E.2. *Presentation of three cost options (low cost, Compromise and Quality).*

Subsystem	A: Low cost	B: Compromise	C: Quality
Head	Microcontroller which registers differances in current baced on the extension of a copper wire. LED's are in single colours	Haptic sensor + LED's in single colours	Haptic sensor + IRA motor+ LED's with colour mixing options
Eyes	No display as eyes (just a 3D printed sqaures), Single Servomotor which delivers torque to turn eyes, the eyes are connected through mechanical motion mechanism (e.g. spur gears) (can be 3D printed)	LCD screen as eyes (rectangular), Single Servomotor which delivers torque to turn eyes, the eyes are connected through mechanical motion mechanism	LCD screens as eyes, two servomotor to turn each eye individually (--> additional degree of freedom allows for more options to express emotions. However, it also comes with a higher weight)
Sensors	Ultrasound sensors + cheap microphone, sensor in thebody, can only detect if something is in front of it. Can still track using camera. Hard software solution	Lidar, radar, microphone: Able to get decent interaction	Lidar, radar, microphone: Able to track a person in a room, read gestures
Control Unit + camer	Arduino + motor control board | Nucleo, cheap camera + remote processing | maybe raspberry pi | Beagle board: Could work but might require several boards and become a mess inside the robot to fit everything.	Raspberry pi 4 + pi cam | Portenta H7 + vision shield: Slightly slower processor but can still do same thing as the most expensive one.	Raspberry pi 4 + jetson nano + pi cam | portenta X8 + vision shield: Good opportunities for advanced tracking
Neck nod general: angle between 0-90deg, min torque of: 0.13Nm	DC motor is mounted at the joint of the neck where it spins to do nodding motion, this solution cuts back on controllability and is a harder solution both to physically fit everything and also to program with an encoder.	Needs to hold a stall torque of 0.13Nm, this solution has better controllability as well as it is easier to program but might not handle interaction good since the motor is not compliant. Could get an external driver to make it compliant but requires more software work.	With a smart compliant motor in the neck, there is no risk of the motor breaking when interacting with the robot, it is also easier to control since it would be the same for all smart motors (if same brand is used for all)
Neck extention: General: Extend head 10 cm, torque needed ~0.1 Nm	Stepper motor/DC motor with encoder + ball screw, simple motor probably takes more space. Control dificulty and many components to be assembled	Another stepper motor + rack pinion -takes more space but higher realibility /accurancy than the first alternative	Extend head(~10cm) with linear actuator Easy to control since smart motor
Base rotation + twist	Servo with encoder + 3D printed gears -lower realibility/accurancy	Servo motor + metallic gears -higher realibility/accurancy	Smart stepper motors for rotation of neck(~+-90degrees) and for rotation of base(360degrees). -very high accurancy
Arms	Cut out from the body with servo motor inside the body: No risk of getting stuck in between. but we lose the ability to have everything closed.	Servo motor + spring loaded rod that extends when the motor turns: the spring prevents getting stuck in between. The arms still extend to some extent but might not look as good as when they extend fully.	Smart compliant servo motor to rotate the arm + linear actuator to extend the arm
Total* (€):	285,86	524,63	2492,953

* Cost for main components, not included: Material for 3D printing, manufacturing cost, cables, ...

Appendix F

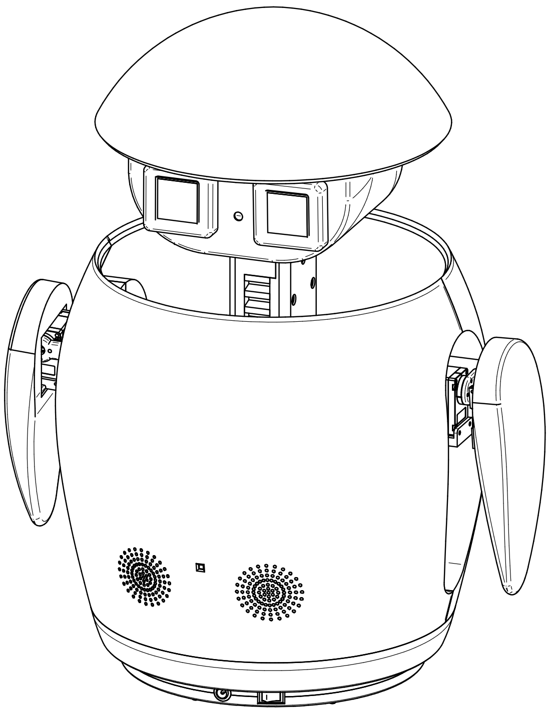
Inventory & Bill of Materials

F.1 Inventory

Table F.1. *Inventory of all components used during the project.*

Item No.	Name	Product Code	Quantity	Price (EUR)	Bought From	Category	Comments
1	USB Cables / IEEE 1394 Cables For UP board	EP-CBUSB10P2FLT	1	6	Mouser	Cable	UP CORE extension
2	Single Board Computers UP board	UPC-CHT01-A10-0464	1	189	Mouser	Development Board - Computer	
3	HXS 50x50x10mm DC 12V Brushless Fan		1	8	ebay	Fan	
4	Miniature 5V Cooling Fan	3368	1	4	adafruit	Fan	
5	MG-90S Metal Gear Micro Servo Motor		2	20	components101	Motor - Servo	
6	ROBOTIS XL330-M288-T	902-0162-000	8	181	robotis	Motor - Smart Servo	
7	Square Force-Sensitive Resistor (FSR)	1075	1	6	adafruit	Sensor - Pressure	
8	Temperature Sensor	3251	1	10	mouser	Sensor - Temperature/Humidity	For Future work to be included
9	ADAFRUIT AMG8833 IR THERMAL CAME	3538	1	44	digikey	Sensor - Thermal Camera	
10	MD-B5014V 5.0 MegaPixel USB QSXGA Camera	CM-1X14U	1	128	shop-wifi	Sensor - Visual Camera	
11	SPEAKER - 40MM DIAMETER - 4 OHM	3968	2	10	digikey	Sound - Speaker	
12	AMP AUDIO 3.7W CLASS D	987	1	9	digikey	Sound - Stereo Amplifier	
13	ROBOTIS XL-430	902-0135-000	1	52	Mouser	Motor - Smart Servo	
14	Logitech keyboard		1			Programming	For Testing
15	Logitech mouse		1			Programming	For Testing
16	U2D2 board	902-0132-000	1	38	Mouser	Motor - Development Board	One of them during testing
17	Usb hub (4 outputs)		1			Cable - management	
18	RS pro Tapered bearing	146-9278	1	5	rs-online	Construction - Bearings	
19	Grove RGB 42 LED Ring 5V	104020173	1	17	Mouser	Visual - LED	
20	"1.3"" 240X240 WIDE ANGLE TFT LCD"	4313	2	33	digikey	Visual - Screen	
21	U2D2 Power Hub Board	902-0145-001	1	22	Mouser	Motor - Hub Board	One of them during testing
22	Power Adaptor (Output 5V, 10A)	658	1	30	adafruit	Power Supply	Needs step up for XL-430
23	Male DC Power Adapter 2.1mm	369	2	4	Mouser	Power - Connector	For easy power to Up-Core
24	Arduino Nano	ABX00033	1	16	rs-online	Development Board	
25	DC-DC boost converter	DFR0123	1	8	Mouser	Power - boost converter	Step up 5v input to 12v
26	3D-printed parts (PLA)		1	77			Price calculated as 100% infill
27	4-Channel Bi Logic Level Eval Board	757	1	4	Mouser	Motor - Level Shifter	
			Total Price of robot:	918			

F.2 Bill of Materials



Item Number	File Name	Material	Quantity
1	10x5x4_Bearing.par		4
2	3968 Speaker 40mm2.par		2
3	AmplifierCard.par		1
4	Arm_Mount.par	PLA	2
5	Base.par	PLA	1
6	Base_lock.par	PLA	1
7	Bearing mount.par	PLA	1
8	Bearing_template.par	PLA	1
9	Body_Back.par	PLA	1
10	Body_Base_flat.par	PLA	1
11	Body_Base_Neckmount.par	PLA	1
12	Body_front.par	PLA	1
13	Bridge.par	PLA	1
14	DC_Boost.par		1
15	Eye_Base.par	PLA	2
16	Eye_Cover.par	PLA	2
17	Eye_Motor_Nut.par	PLA	2
18	Female DC-Power-to-Screw-Terminals-Adapter.par		1
19	gear_m3_t10_idler.par	PLA	1
20	gear_m3_t10_motor.par	PLA	1
21	Gear_V2.par	PLA	1
22	Hat inside_V2.par	PLA	1
23	Hat_V3.par	PLA	1
24	Head.par	PLA	1
25	Knob.par	Silicone	6
26	LED-ring.par		1
27	lock_rackpath.par	PLA	2
28	m1,8_10_cap.par	Stainless steel	2
29	m2_3_cap.par	Stainless steel	2
30	m2_5_cap.par	Stainless steel	6
31	m2_6_cap.par	Stainless steel	4
32	M2_7.9mm.par		8
33	m2_8_cap.par	Stainless steel	4
34	m3_10_cap.par	Stainless steel	10
35	m3_12_cap.par	Stainless steel	4
36	m3_16_cap.par	Stainless steel	3
37	m3_20_cap.par	Stainless steel	6
38	m3_30_cap.par	Stainless steel	7
39	m3_40_cap.par	Stainless steel	8
40	m3_4_cap.par	Stainless steel	2
41	m3_6_cap.par	Stainless steel	8
42	m3_8_cap.par	Stainless steel	24
43	MG90SBody.par		2
44	Motor_holder.par		2
45	Nano_plus_case.asm		1
46	Neck_Mount_Motor.par	PLA	1
47	Neck_Mount_Pin.par	PLA	1
48	Neck_Rack.par	PLA	2
49	Neck_Slider.par	PLA	1
50	Neck_Slider_Stop.par	PLA	2
51	Neck_Tube.par	PLA	1
52	Neck_Tube_No_Motor.par	PLA	1
53	newArms.par	PLA	2
54	PCB Component.asm		2
55	pcb CoreUp.asm		1
56	Pinion.par	PLA	1
57	pinion_1.par	PLA	2
58	Pressure sensor.par		1
59	rack_v2.par	PLA	2
60	RackPath.par	PLA	2
61	Rotation Attachment_new.par	PLA	2
62	Support LED-ring.par		2
63	Switch button.par		1
64	Thermal Camera.par		1
65	U2D2.asm		1
66	USB_Hub.asm		1
67	XL,XC-330.asm		1
68	XL,XC-330.asm		1
69	XL330-Body.asm		4
70	XL330-fronsplines.asm		2
71	XM,H-430_idler.asm		1

BOM of FUYU Robot
Total parts: 183

Detaljnr	Antal	Benämning	Material	Anmärkning	
Skapad av		Godkänd av	Material	Ersätter	Ersatt av
MF2058		FUYU		Datum 2022-12-01	
				Ritningsnr	

Appendix G

Software

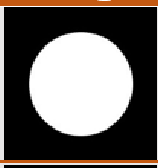
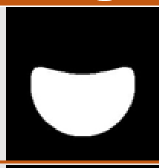
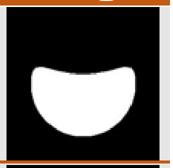
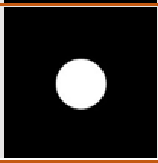
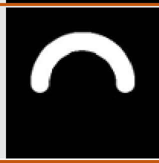
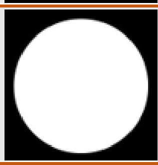
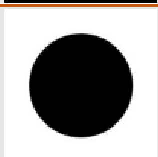
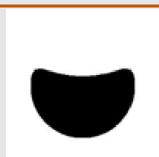
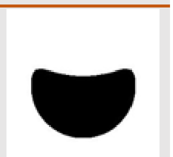
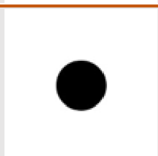
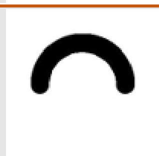
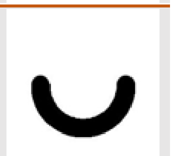
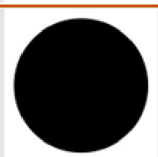
G.1 Used Libraries

Library/Software	Author/publisher	Used For	Used on	Notes
Wire	Arduino	Enables for I2C communication	Arduino Nano	
AMG88xx	Adafruit	Driving the thermal camera	Arduino Nano	
Teensyduino	PJRC	Arduino IDE Teensy compatability	Teensy 4.0	Software extension, not a library
Servo	Arduino	Driving the MG90 servo motors	Teensy 4.0	Teensyduino Port of the library was used
ST7735_t3	Paul Stoffregen	Driving the eye displays	Teensy 4.0	Teensy specific library
Adafruit_GFX	Adafruit	Driving the eye displays	Teensy 4.0	
SD	Arduino	Reading bitmaps from the sd card	Teensy 4.0	Teensyduino Port of the library was used
SPI	Arduino	Enables I2C communication	Teensy 4.0	Teensyduino Port of the library was used
FastLED	Daniel Garcia	Driving the head LED ring	Teensy 4.0	Teensyduino Port of the library was used
Servo	Arduino	Driving the MG90 servo motors	Teensy 4.0	Teensyduino Port of the library was used
Serial	Arduino	Easy µC serial comunication	Arduino + Teensy	Teensyduino Port was used on the Teensy
LinuxCppSerial	gbmhunter	Easy linux serial comunication	Up-Core	
DynamixelSDK	ROBTIS	DYNAMIXEL motor control	Up-Core	
OpenCV	OpenCv	Computer vision facial detection	Up-Core	v4.6.0

G.2 Defined Serial Messages

FROM	TO	MESSAGE	TAG		DATA SIZE	DATA					
			decimal	char	bytes	byte 0	byte 1	byte 2	byte 3	...	byte end
UpCore	Teensy	Set LED ring RGB color	76	L	4	Red	Green	Blue	Unused		
UpCore	Teensy	Set left eye motor pos	77	M	4	High	...	...	Low		
UpCore	Teensy	Set right eye motor pos	78	N	4	High	...	...	Low		
UpCore	Teensy	Set display image	68	D	1	Image ID					
Teensy	UpCore	Signal that head button is pushed	98	b	1	Unused					
UpCore	Nano	Play audio	83	S	1	Audio ID					
UpCore	Nano	Request thermal camera image	84	T	1	Unused					
Nano	UpCore	Send thermal camera data	116	t	64	Pixel 0	Pixel 1	Pixel 2	Pixel 3	...	Pixel 63

G.3 Defined Eye Graphics

Implemented Eye Graphics					
ID	Image	ID	Image	ID	Image
65		66		67	
68		69		70	
71					
97		98		99	
100		101		102	
103					
0					

G.4 Processor Summary

UP Core
Main processor Running Ubuntu
- Controls all high level robot functions
- Controls Dynamixel motors using dynamixel SDK
- Connected to visual camera via USB
- Runs OpenCV for facial detection
- Controls slave processors via serial commands
Teensy 4.0
Slave microcontroller controlling interactrion components
- Drives eye motors following recieved serial commands
- Drives eye displays following recieved serial commands
- Drives head LEDs following recieved serial commands
- Reads state of head button and sends signal UP Core if it is pushed
Arduino Nano
Slave microcontroller controlling interactrion components
- Drives speakers following recieved serial commands
- Reads thermal camera following recieved serial commands
- Sends thermal camera data to UP Core if requested

Appendix H

Questionnaire

H.1 Questionnaire 1

The emotionally expressive robot

In the course MF2059, Mechatronics advanced course, our task was to create a robot that could express emotions. Using Haru, the social robot project led by Honda Research Institute of Japan, as inspiration, we developed an emotionally expressive robot.

Below are a number of questions that we would like you to answer, to help our research.The first part consist of videos where you write your answer, the second part will contain the same videos, but the answers will be given in checkboxs.

NOTE: The following media is strictly confidential and is not permitted to be shared or reproduced.

*Obligatorisk

1. Have you seen the final presentation 2022-12-12? *

   Markera endast en oval.

   ◯ Yes
   ◯ No

2. Your age *

   ____

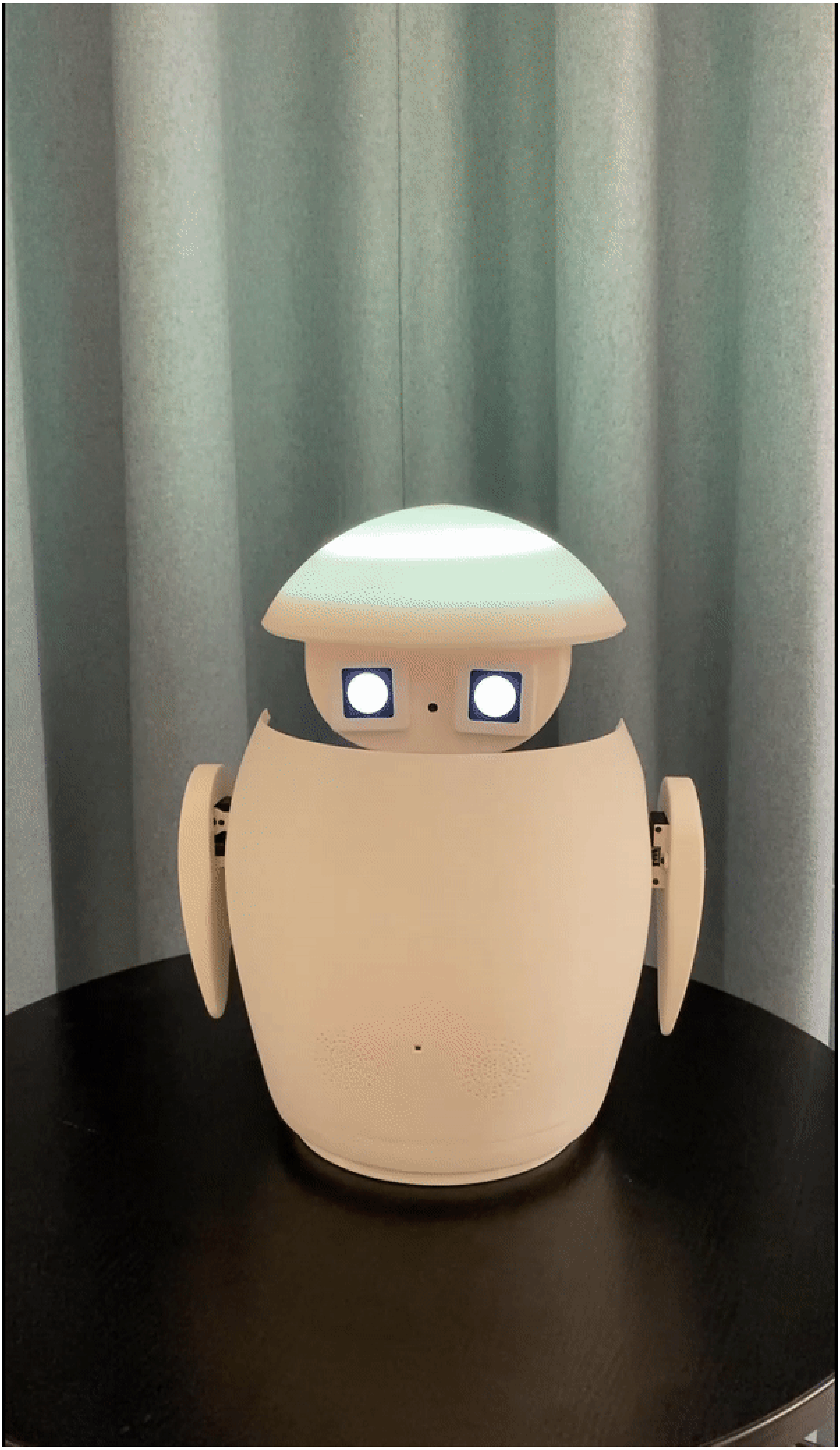
3. Which country are you from?

   ____

4. Which emotion do you associate with video nr 1?

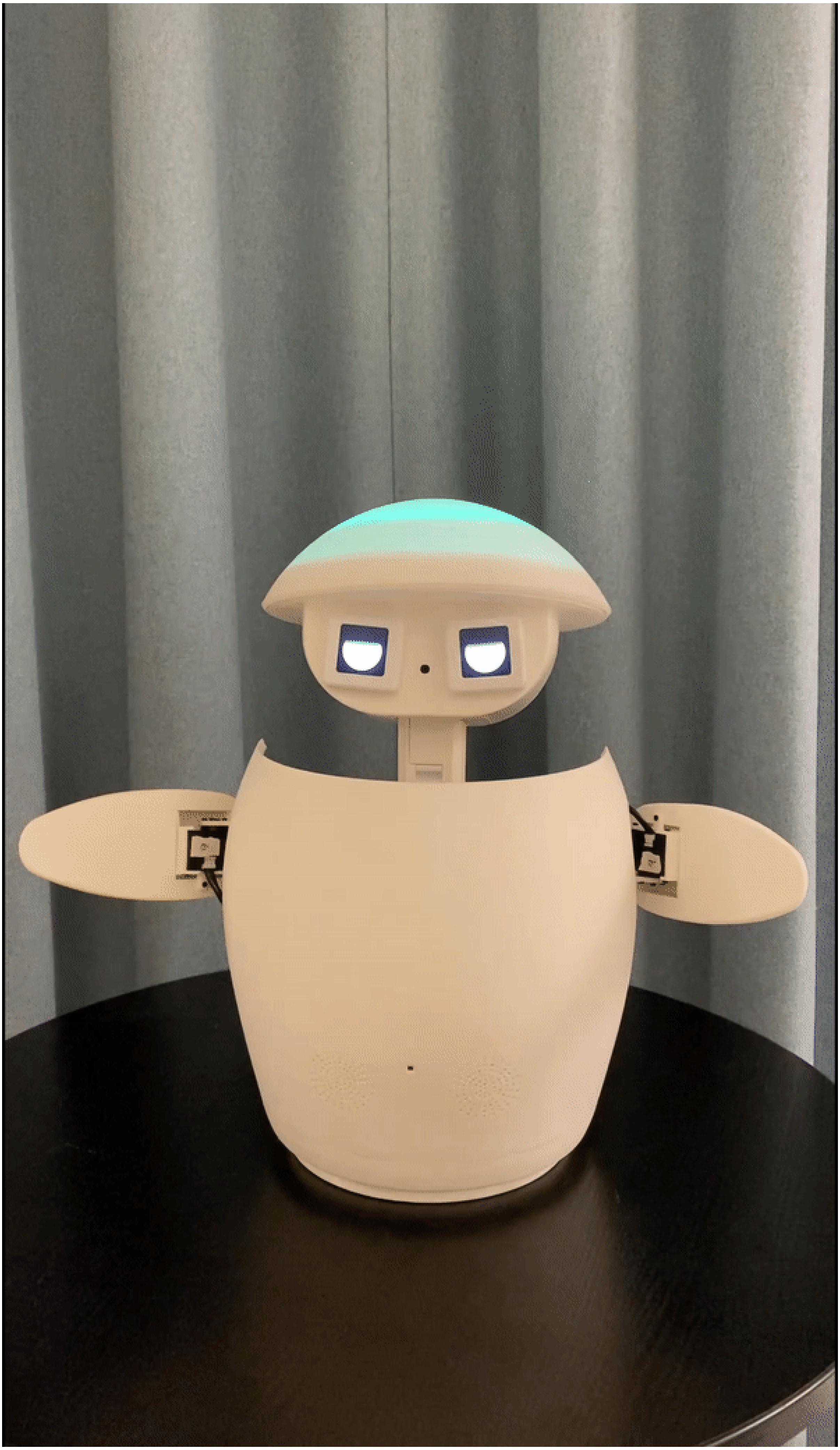
   ____

Video nr 1



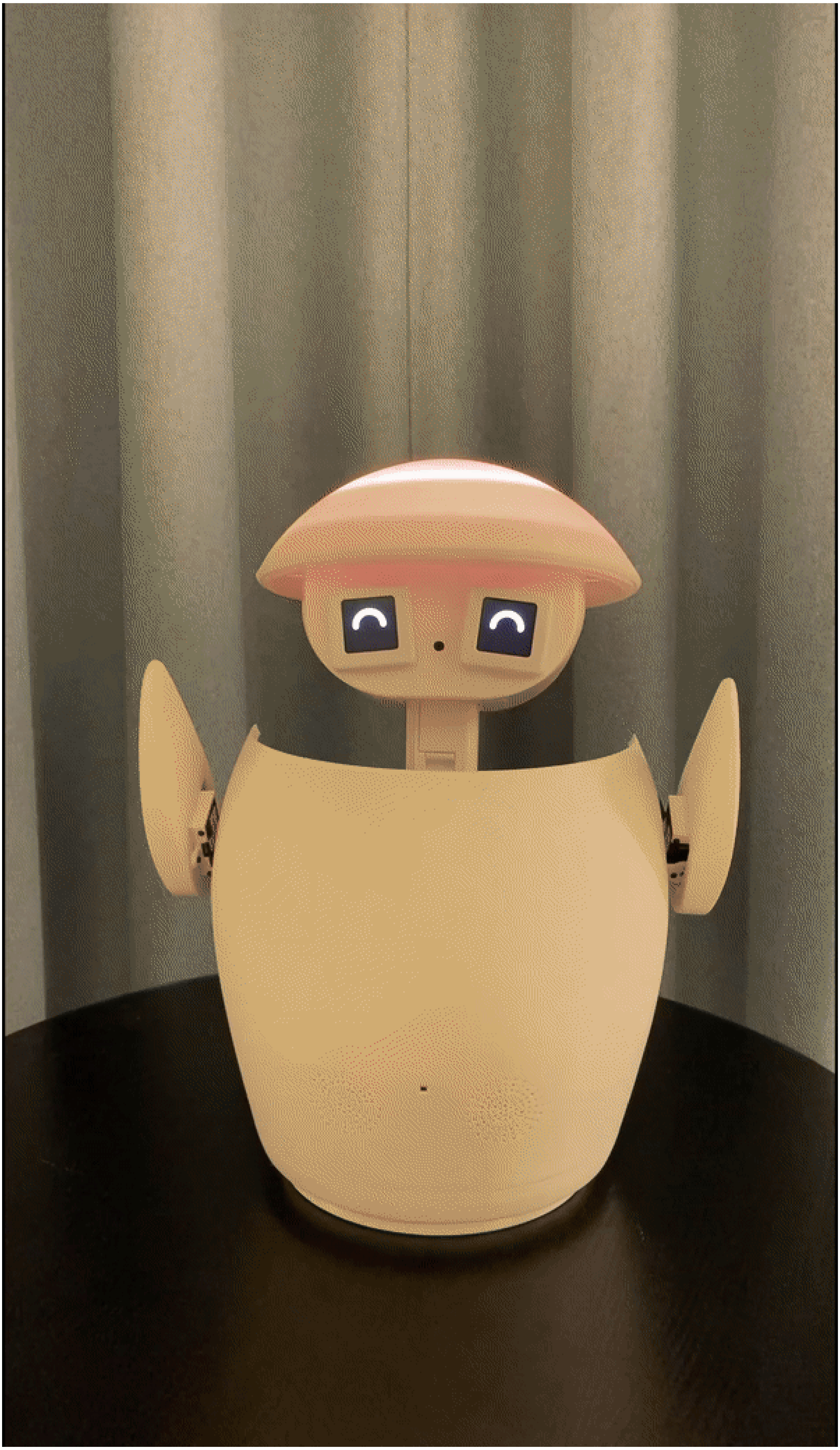
5. Which emotion do you associate with video nr 2?

Video nr 2



6. Which emotion do you associate with video nr 3?

Video nr 3

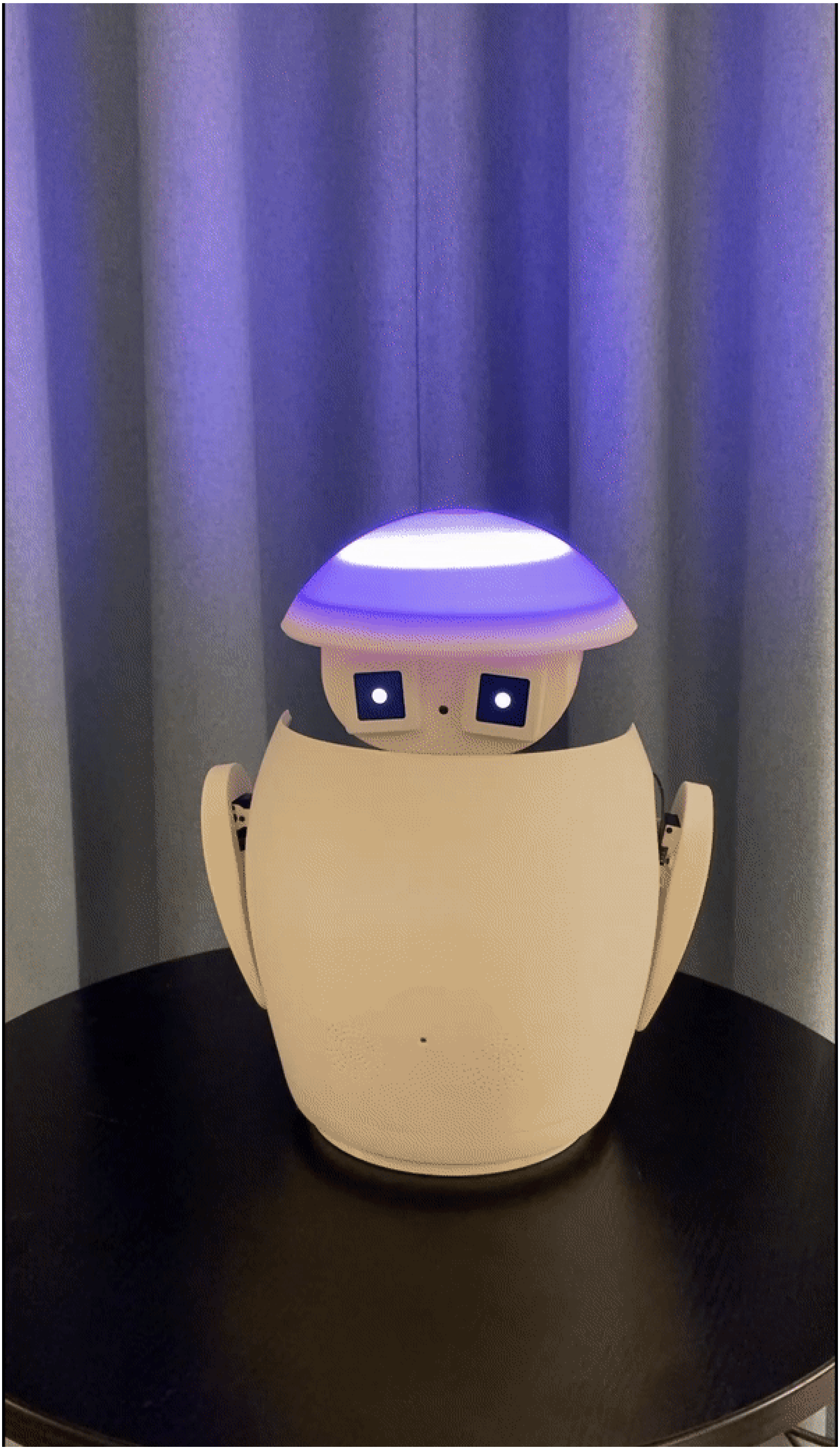


7. Which emotion do you associate with video nr 4?

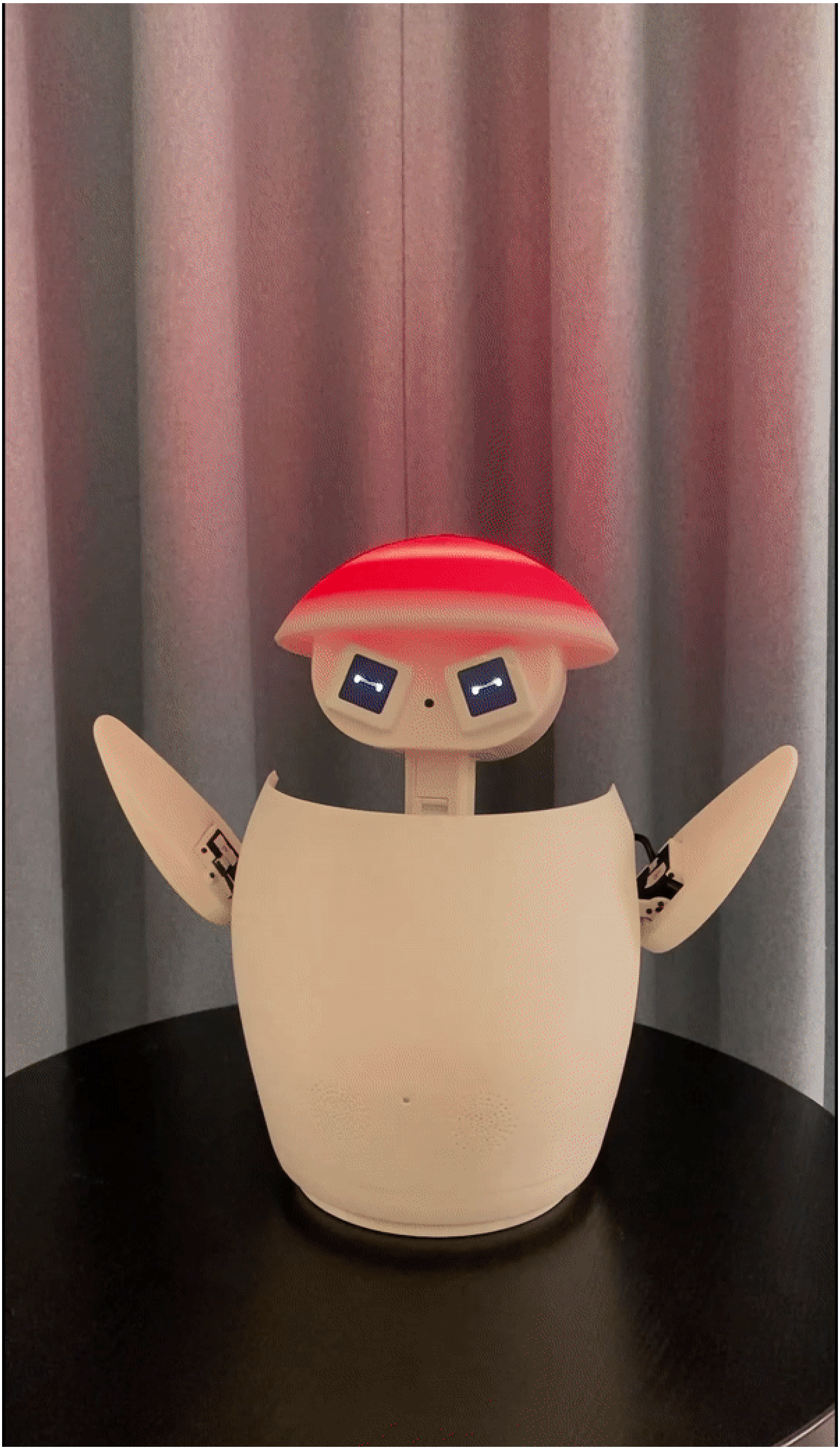
Video nr 4

8. Which emotion do you associate with video nr 5?

Video nr 5



9. Which emotion do you associate with video nr 6?



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10. Which emotion do you associate with video nr 1?

Markera endast en oval.

- Happy
- Sad
- Angry
- Disgust
- Surprised
- Shy

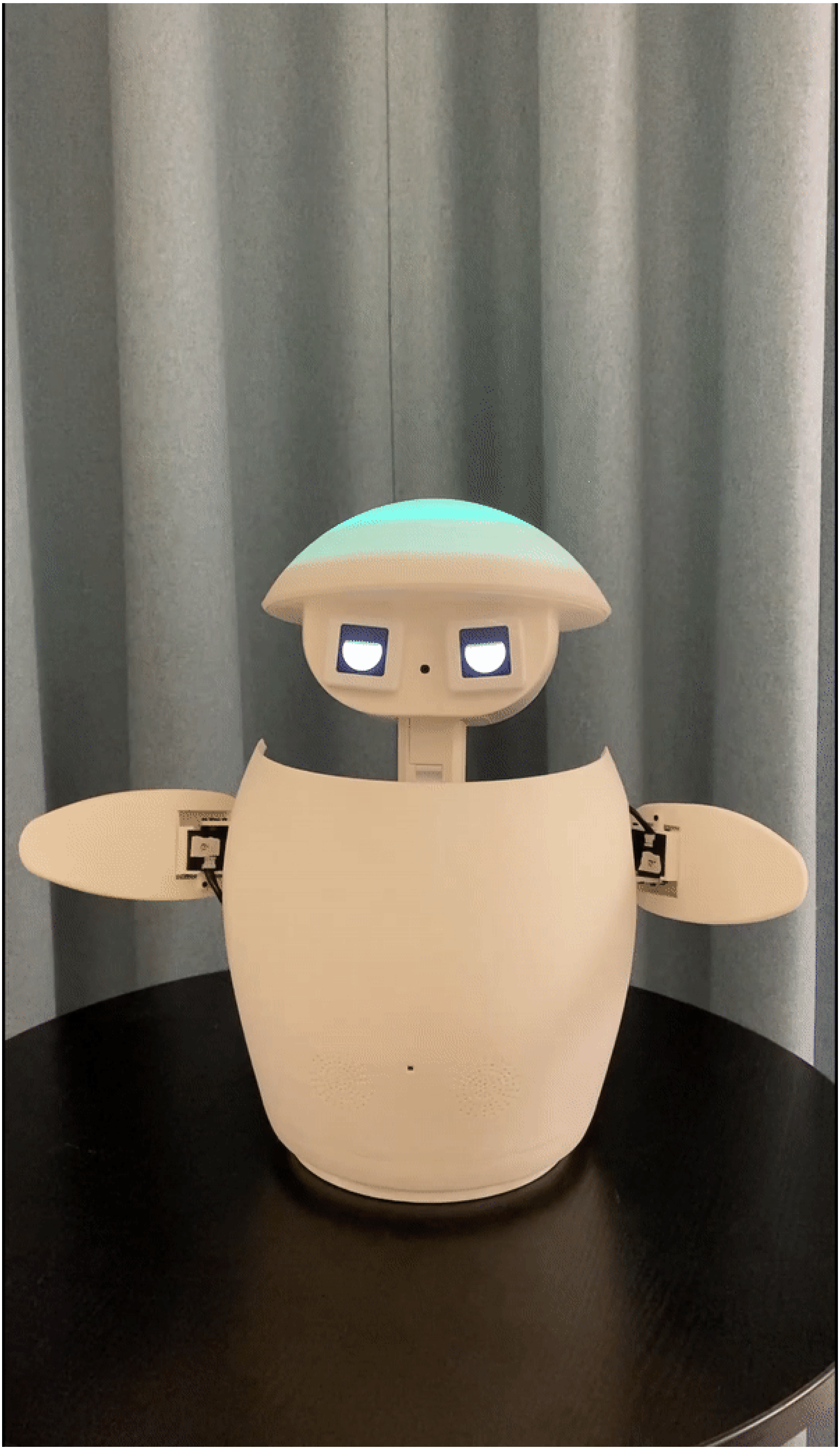
Video nr 1

11. Which emotion do you associate with video nr 2?

Markera endast en oval.

- ⬭ Happy
- ⬭ Sad
- ⬭ Angry
- ⬭ Disgust
- ⬭ Surprised
- ⬭ Shy

Video nr 2

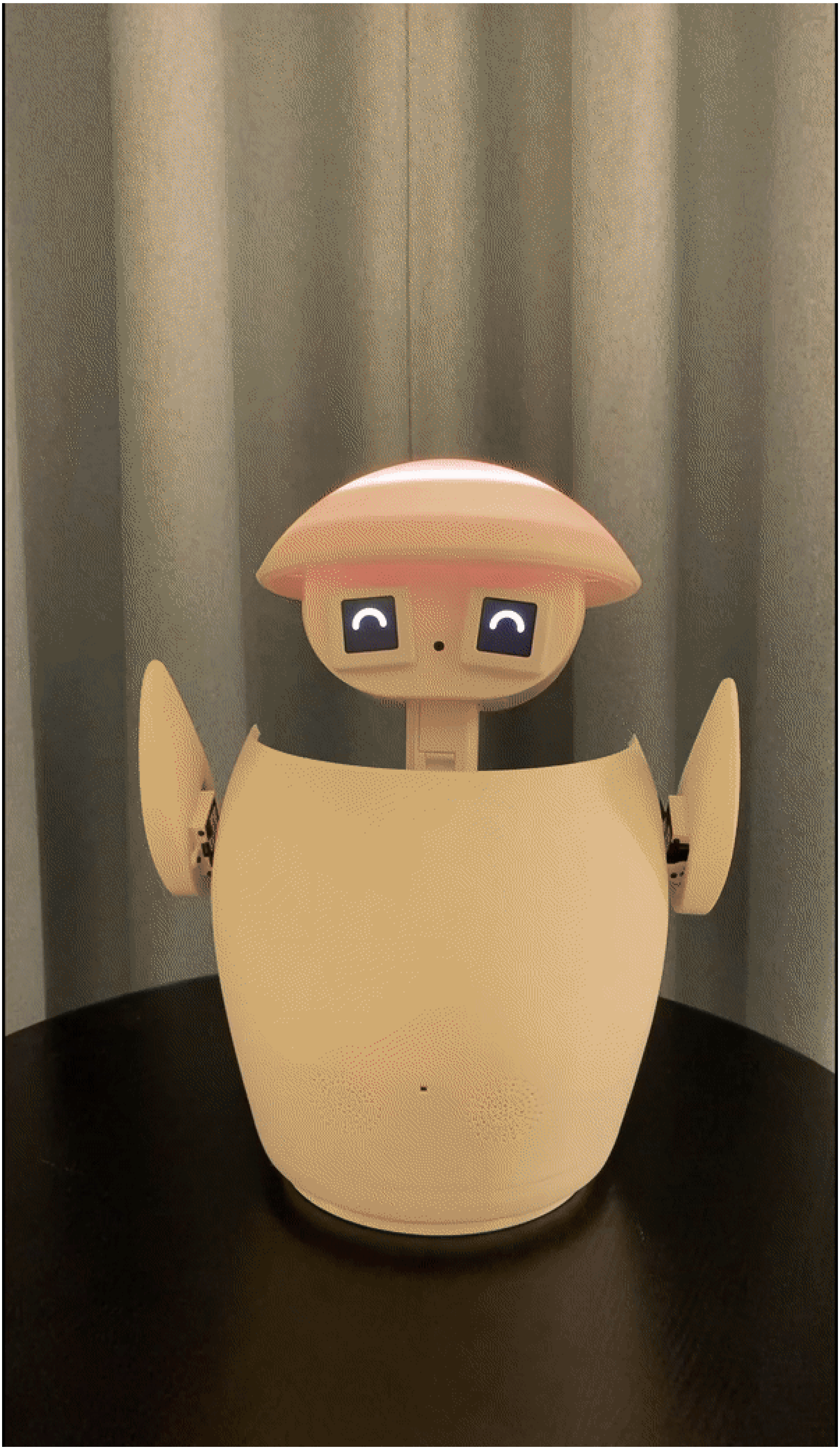


12. Which emotion do you associate with video nr 3?

Markera endast en oval.

- Happy
- Sad
- Angry
- Disgust
- Surprised
- Shy

Video nr 3

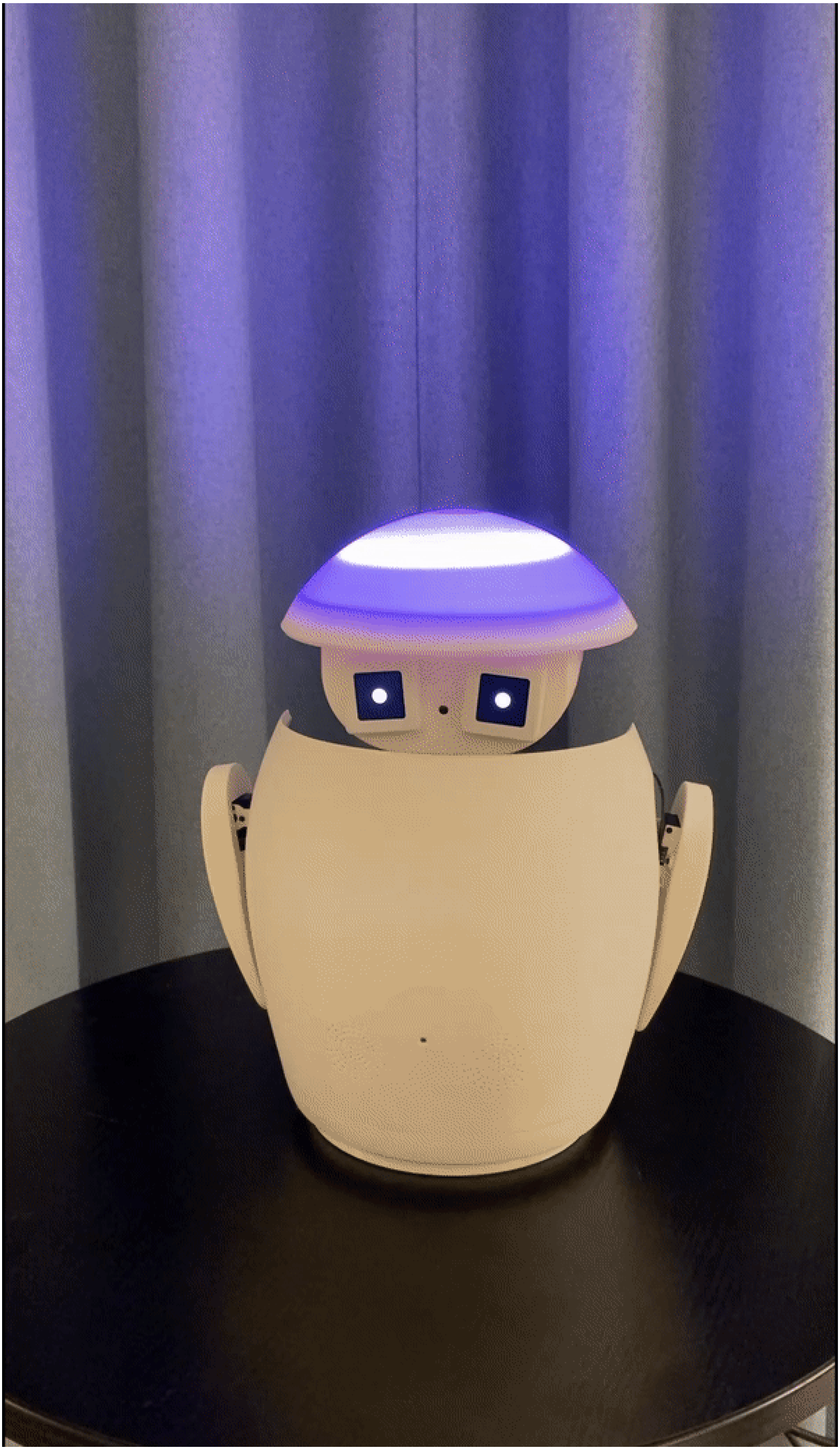


13. Which emotion do you associate with video nr 4?

Markera endast en oval.

- Happy
- Sad
- Angry
- Disgust
- Surprised
- Shy

Video nr 4

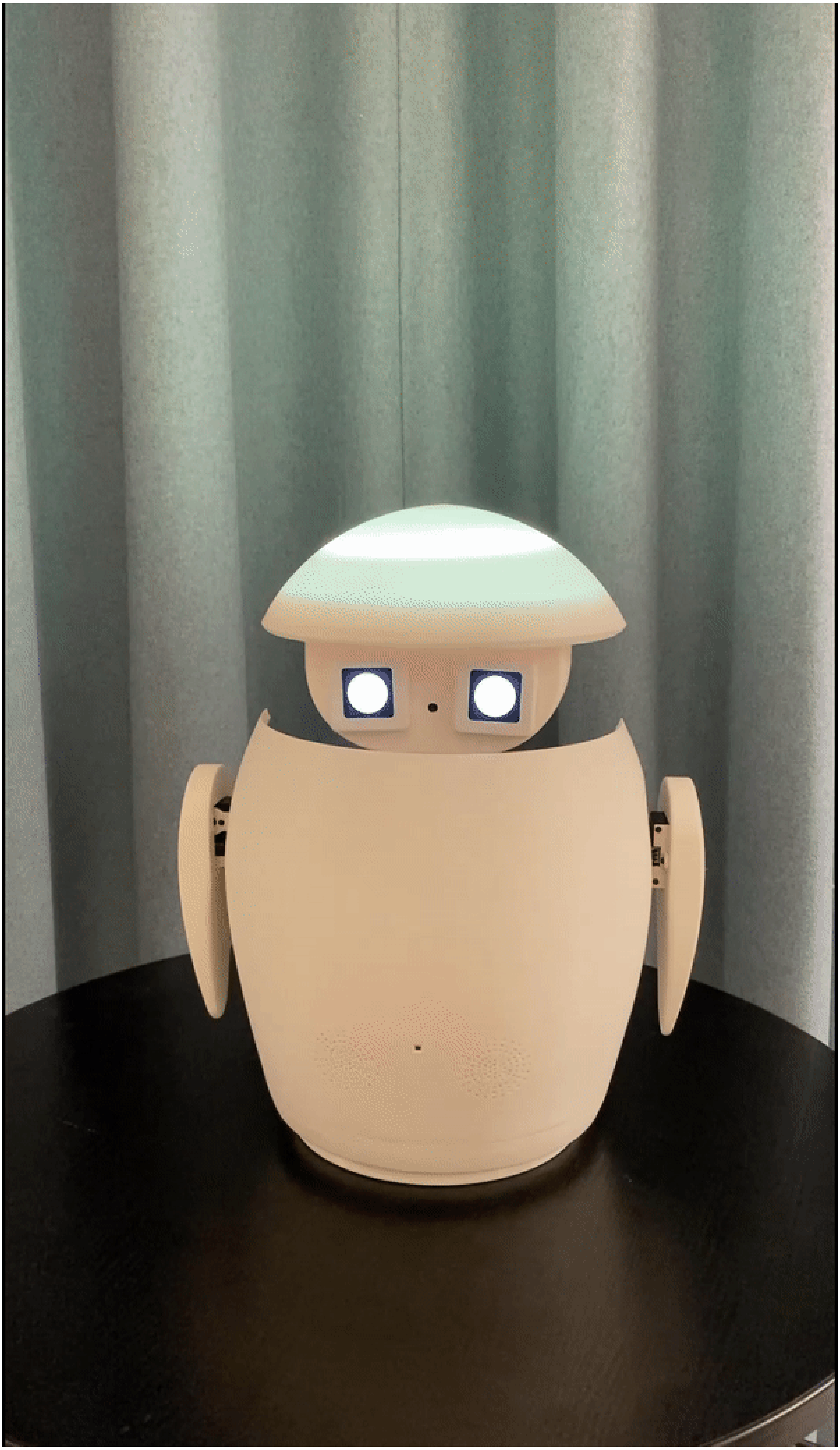


14. Which emotion do you associate with video nr 5?

Markera endast en oval.

- Happy
- Sad
- Angry
- Disgust
- Surprised
- Shy

Video nr 5

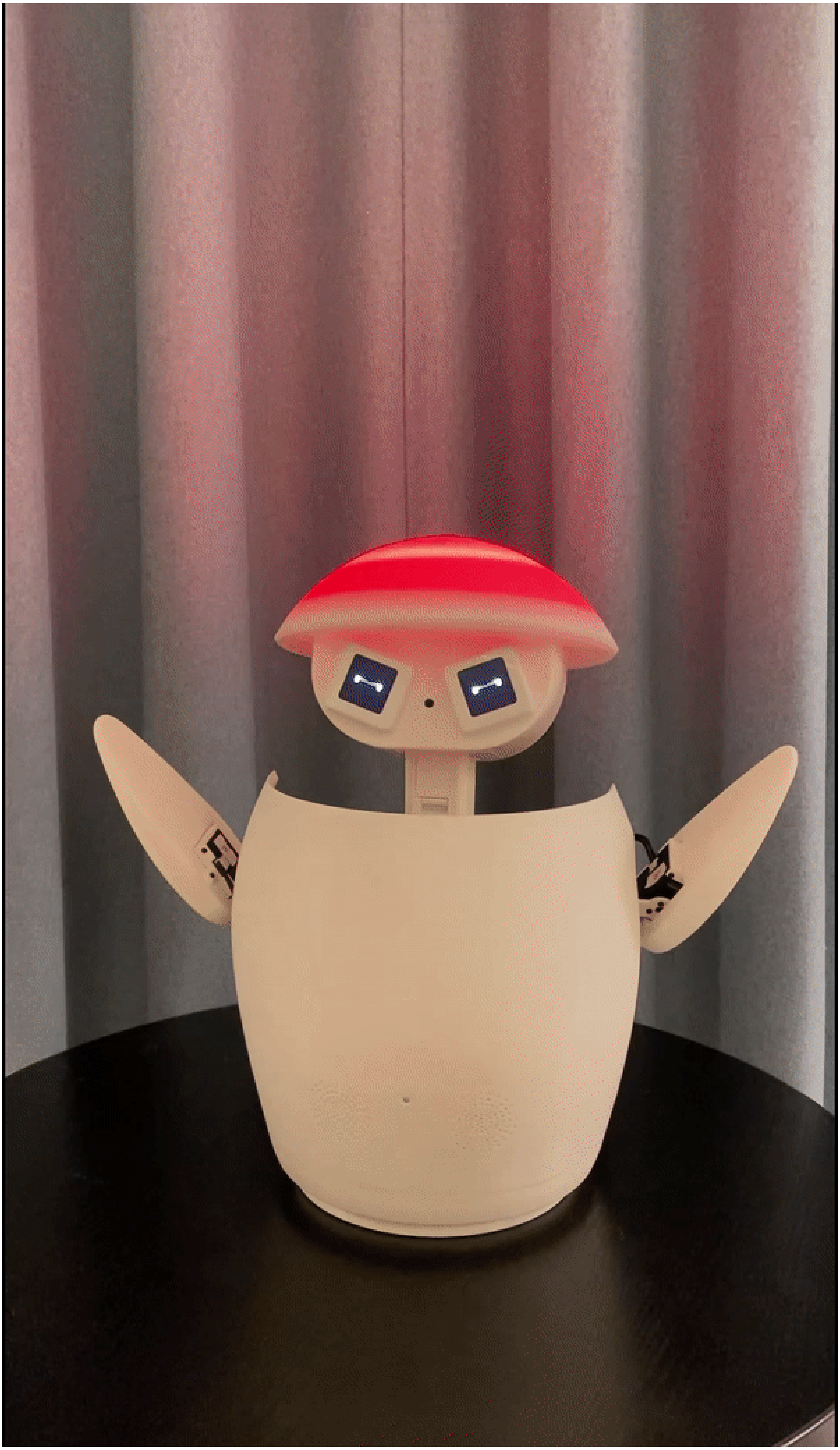


15. Which emotion do you associate with video nr 6?

Markera endast en oval.

- Happy
- Sad
- Angry
- Disgust
- Surprised
- Shy

Video nr 6



H.1.1 Questionnaire 1, Age result

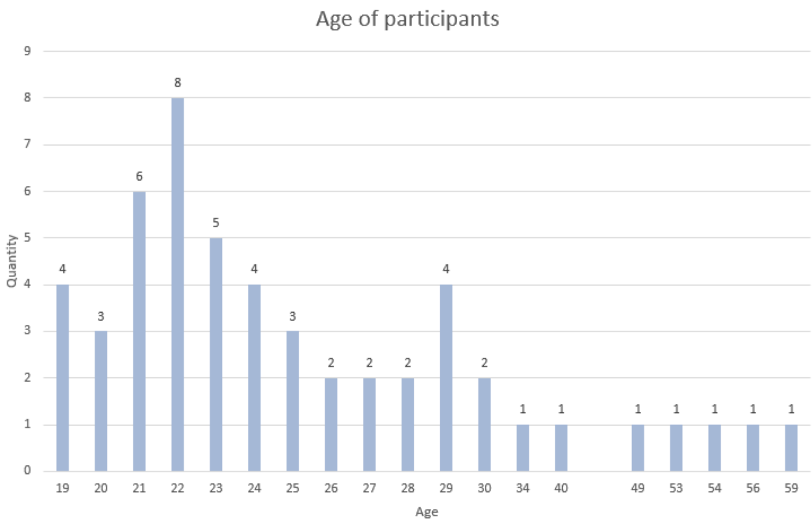


Figure H.1. *A bar-chart showing the age of the 52 participants. Bar-chart made in Excel.*

H.1.2 Questionnaire 1, Country result

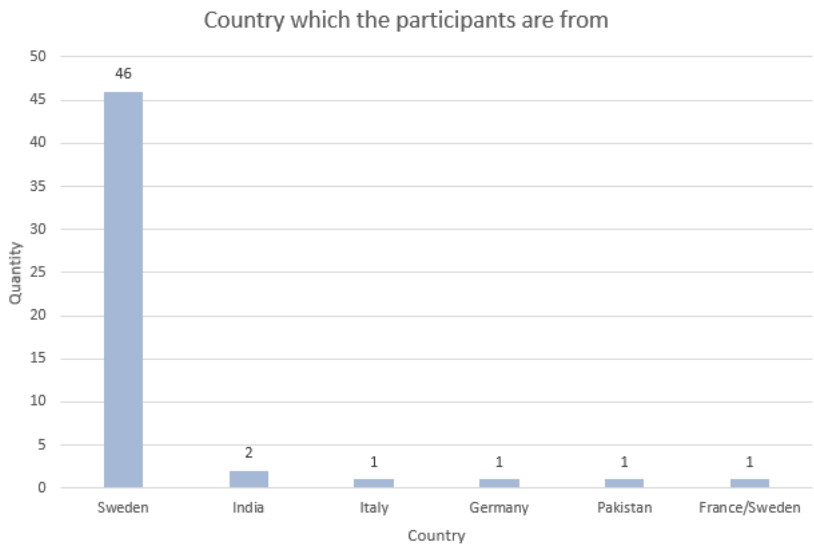


Figure H.2. *A bar-chart showing which country the 52 participants came from. Bar-chart made in Excel.*

H.1.3 Questionnaire 1, Seen final presentation

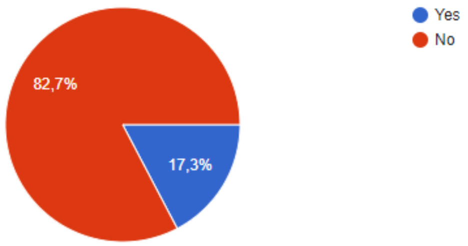


Figure H.3. A pie-chart showing how many of the participants that had seen the final presentation. Pie-chart made in Excel.

H.2 Questionnaire 2

The emotionally expressive robot

In the course MF2059, Mechatronics advanced course, our task was to create a robot that could express emotions. Using Haru, the social robot project led by Honda Research Institute of Japan, as inspiration, we developed an emotionally expressive robot.

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NOTE: The following media is strictly confidential and is not permitted to be shared or reproduced.

*Obligatorisk

1. Have you seen the final presentation 2022-12-12? *

   Markera endast en oval.

   ◯ Yes

   ◯ No

2. Your age *

   ____

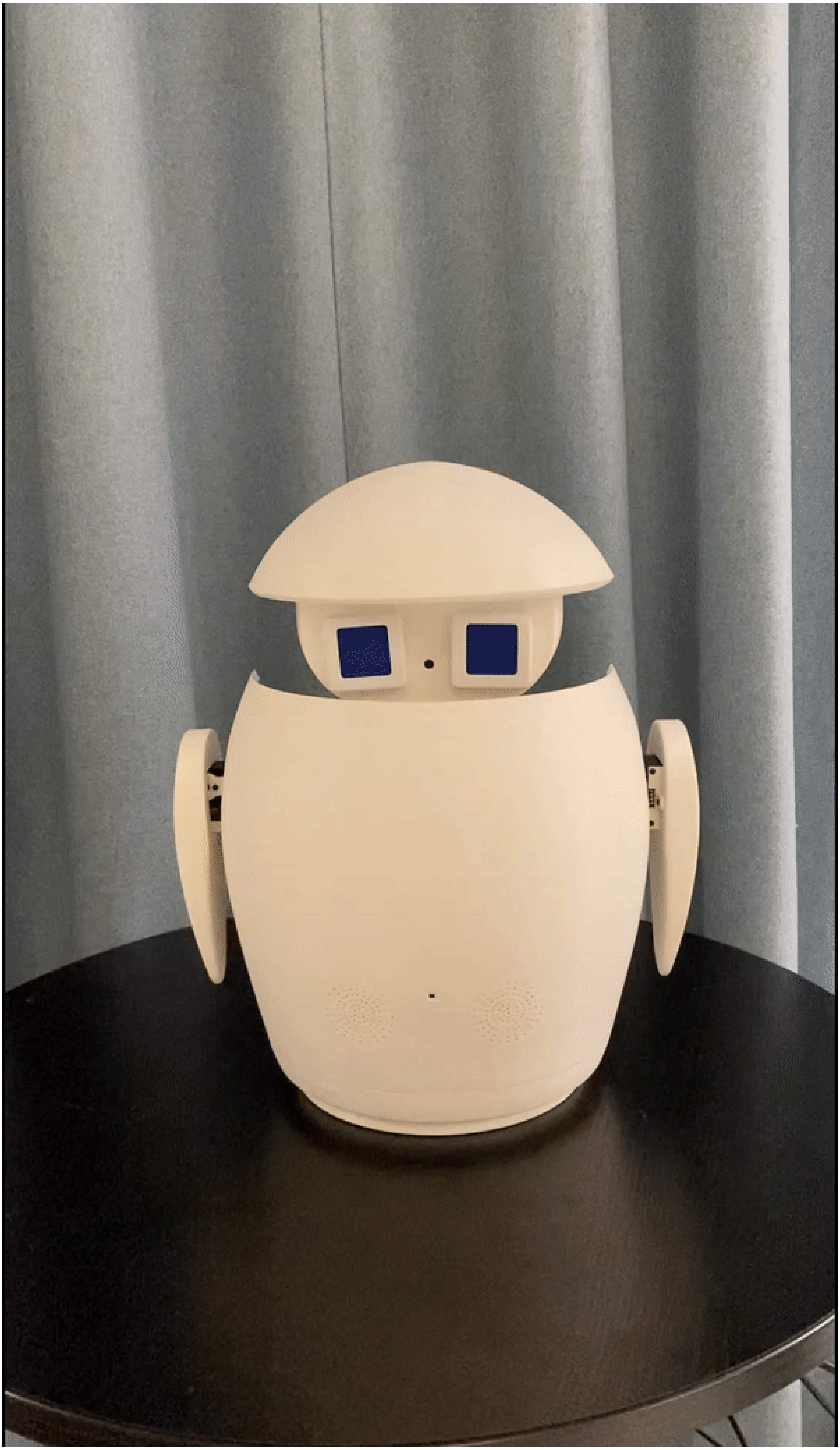
3. Which country are you from?

   ____

4. Which emotion do you associate with video nr 1?

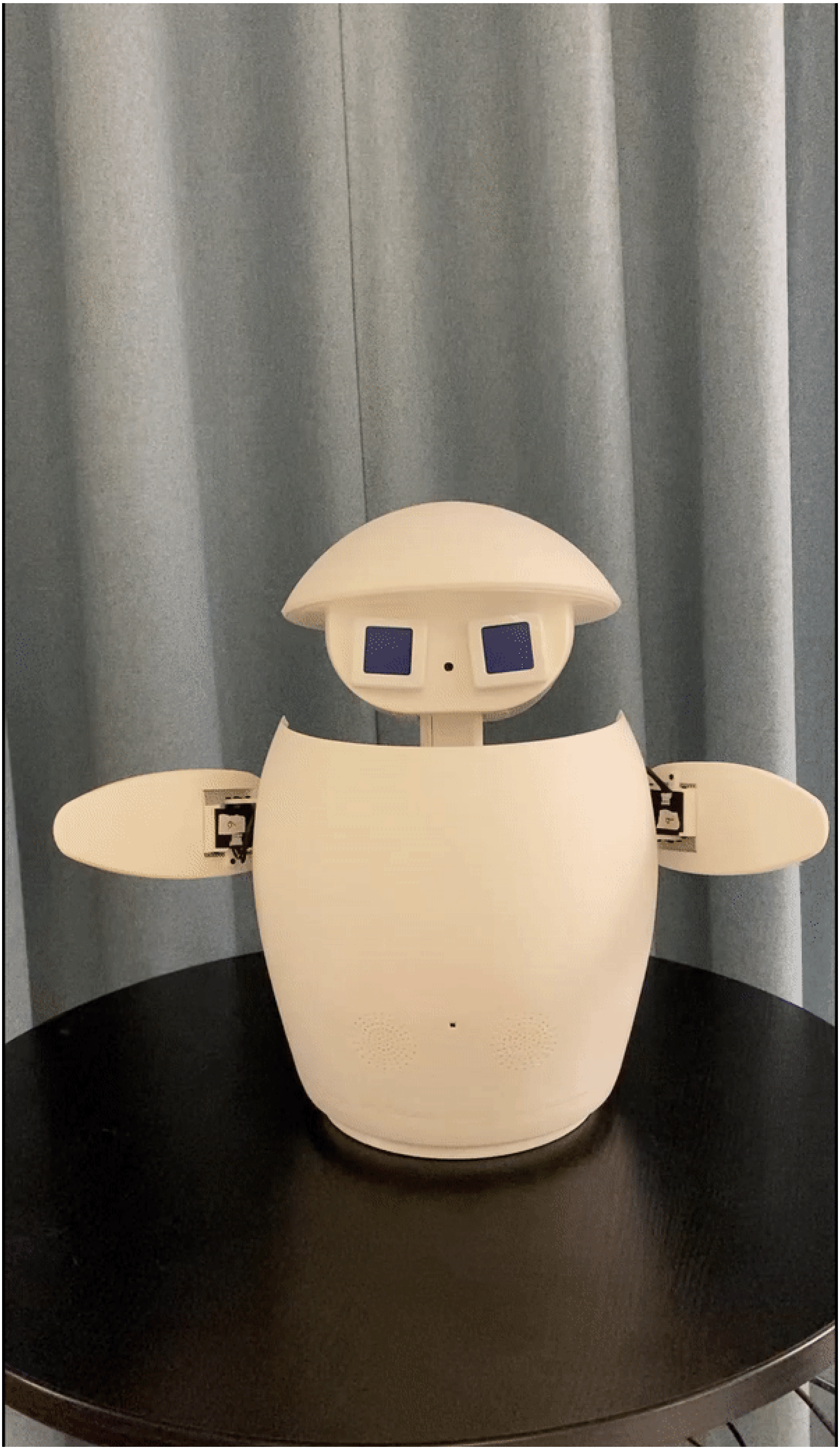
   ____

Video nr 1



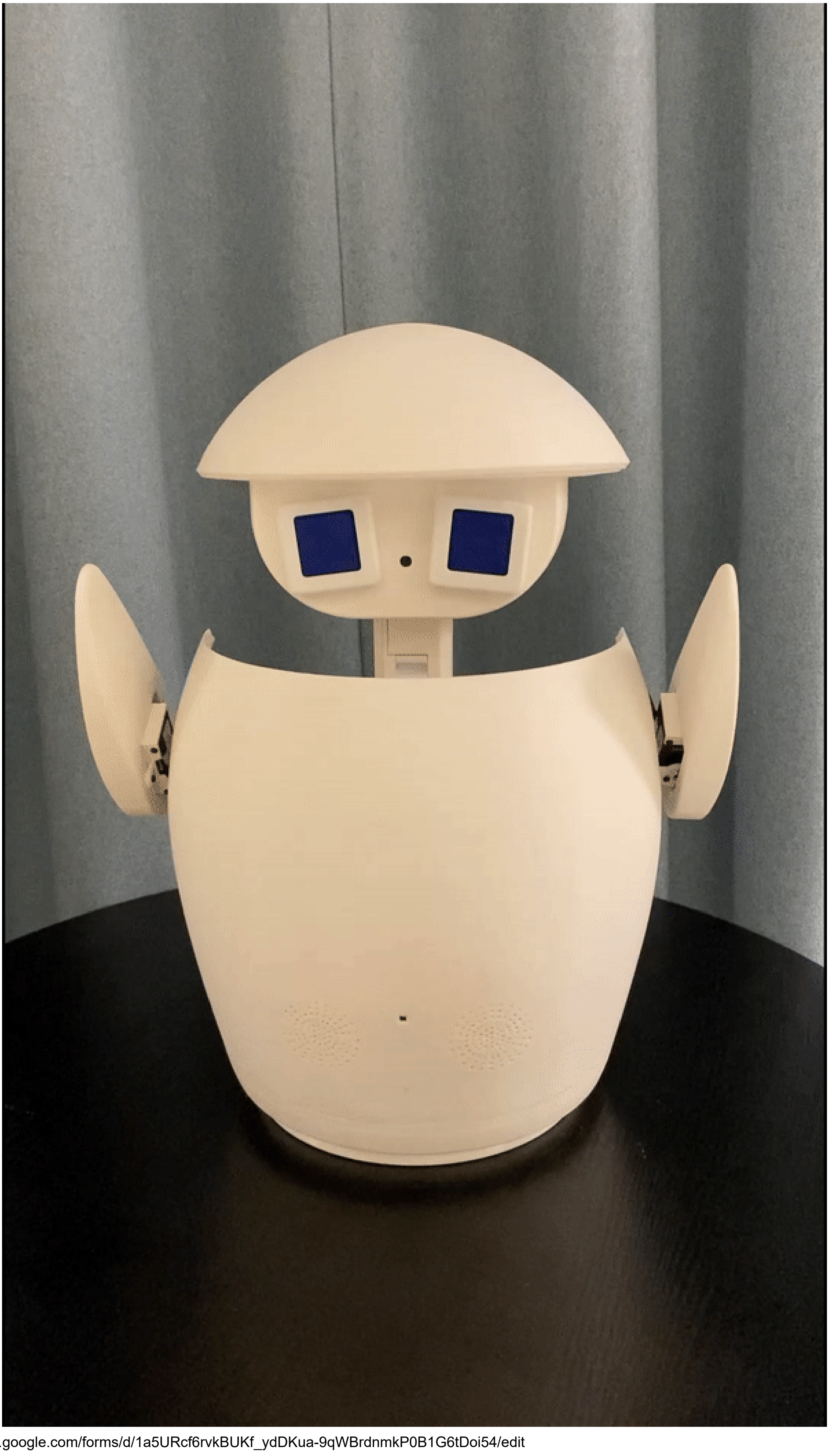
5. Which emotion do you associate with video nr 2?

Video nr 2



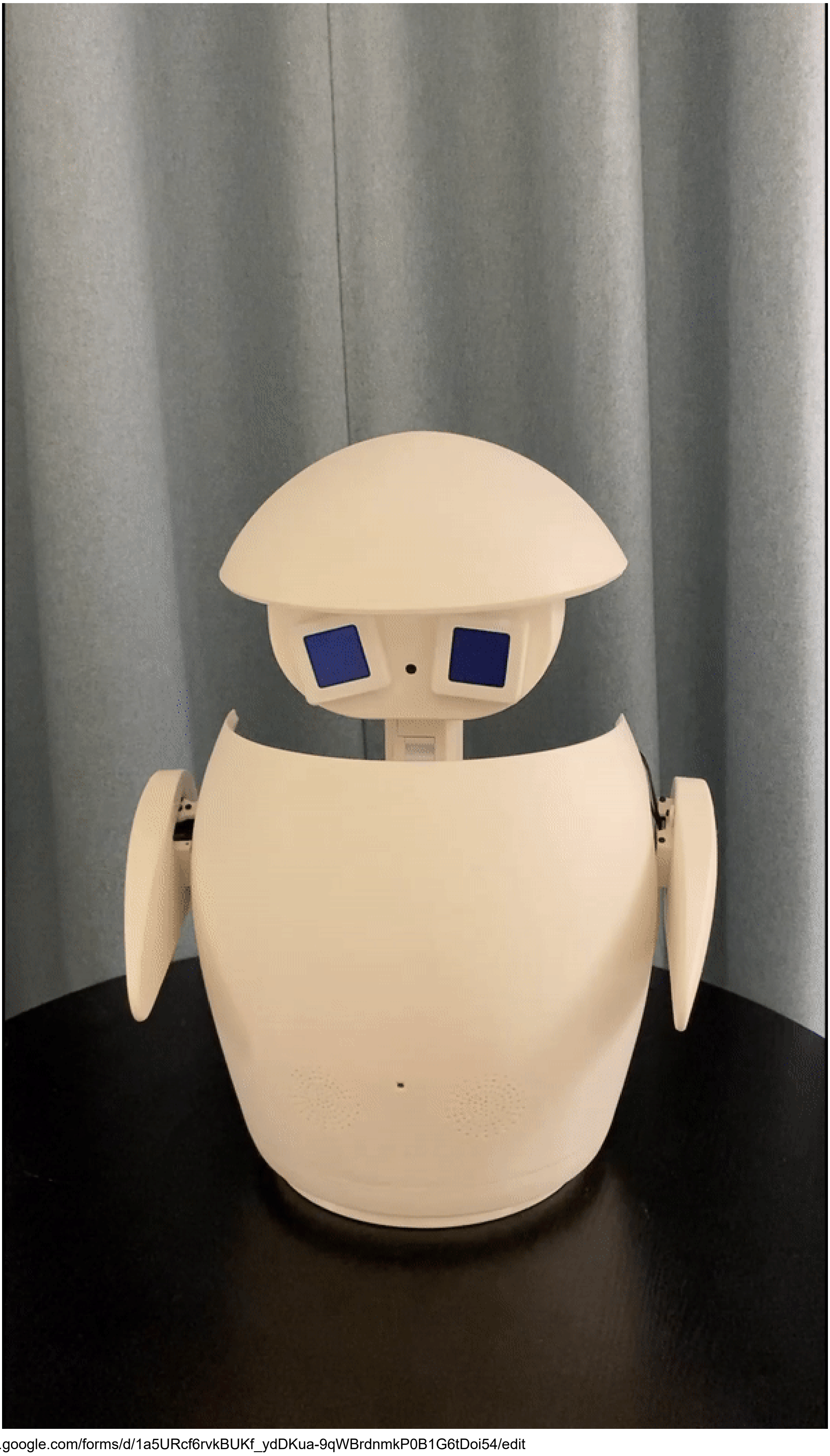
6. Which emotion do you associate with video nr 3?

Video nr 3



7. Which emotion do you associate with video nr 4?

Video nr 4

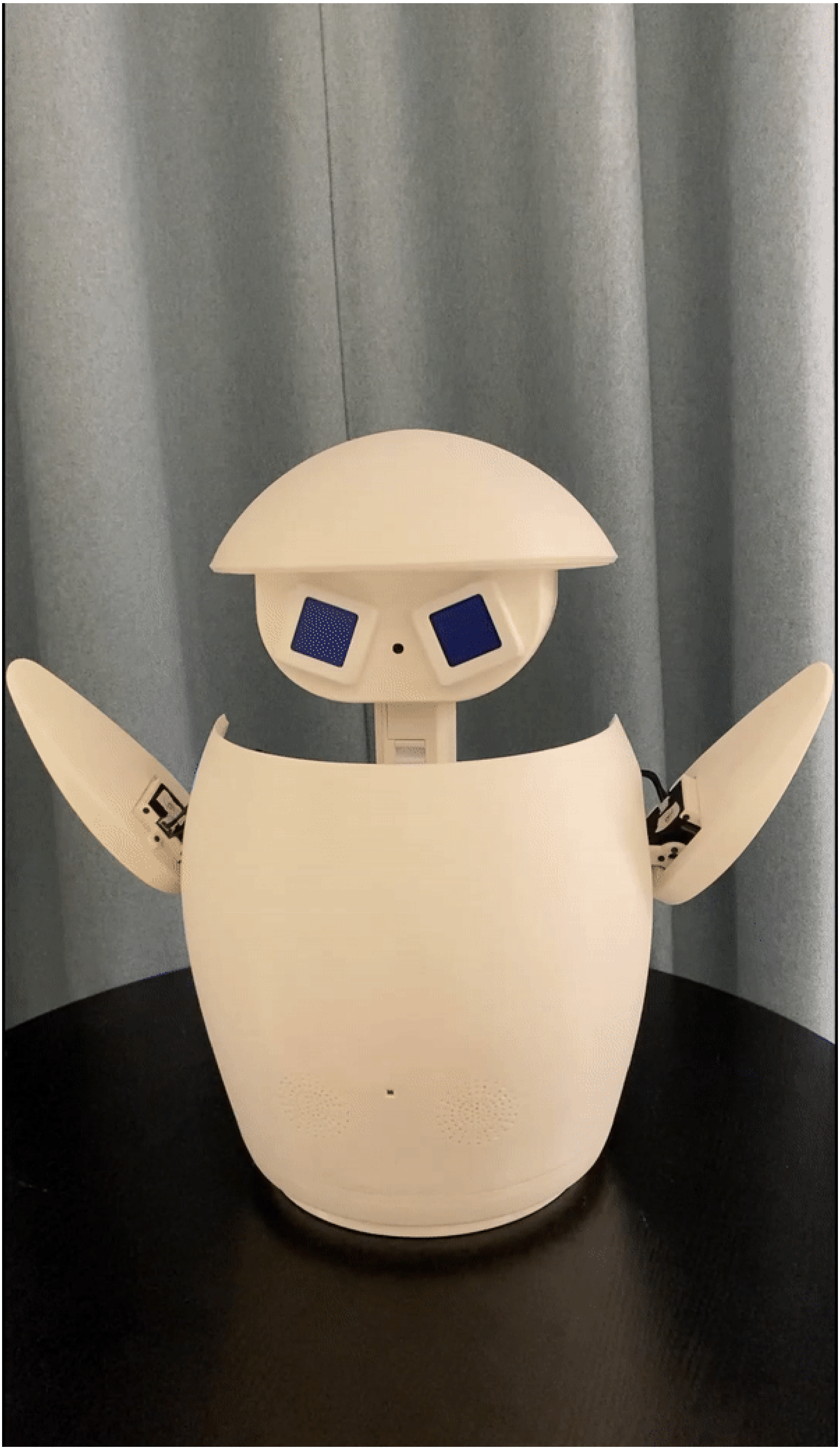


8. Which emotion do you associate with video nr 5?

Video nr 5

9. Which emotion do you associate with video nr 6?

Video nr 6



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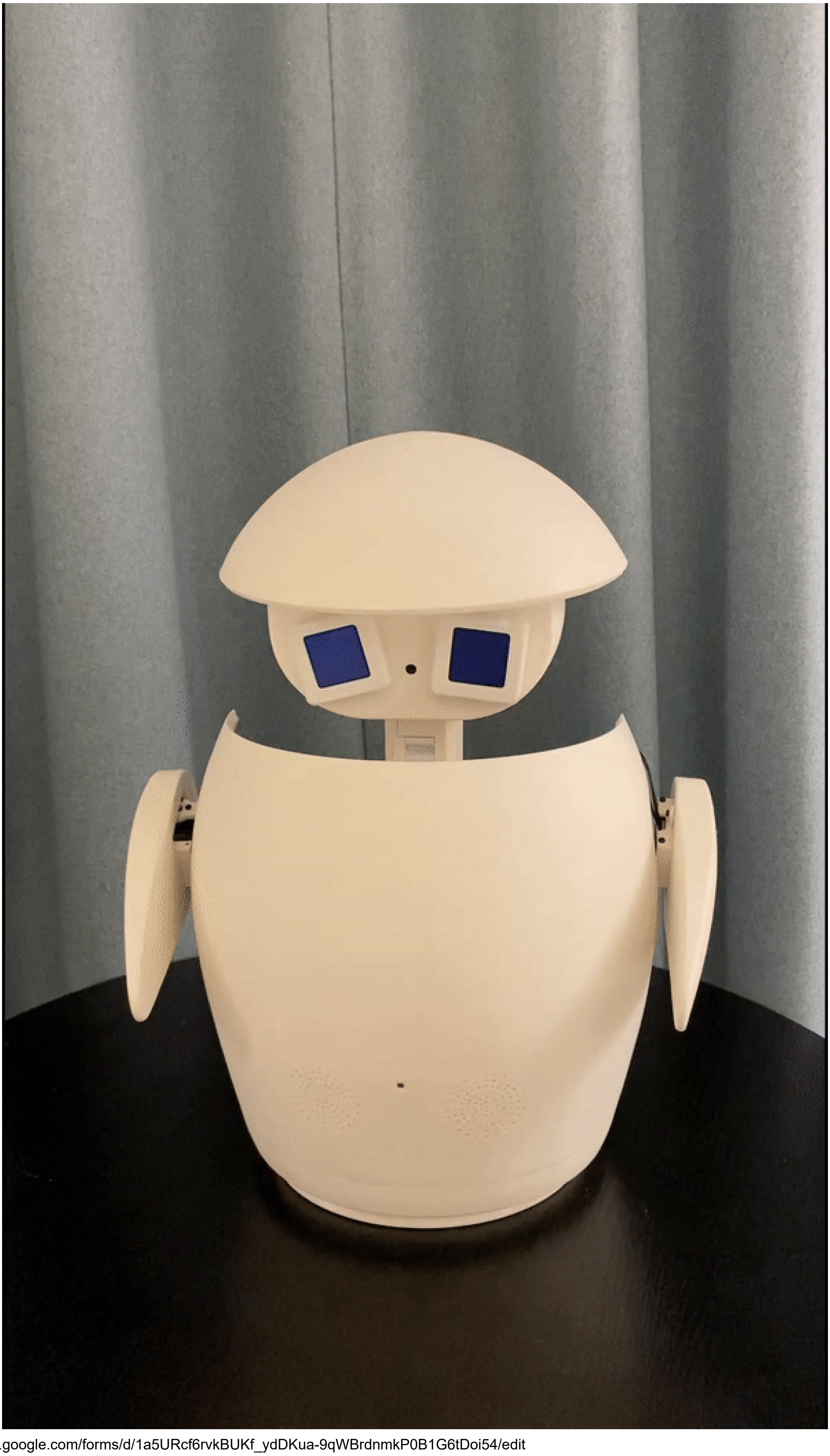
10. Which emotion do you associate with video nr 1?

Markera endast en oval.

- Happy
- Sad
- Angry
- Disgust
- Surprised
- Shy

Video nr 1

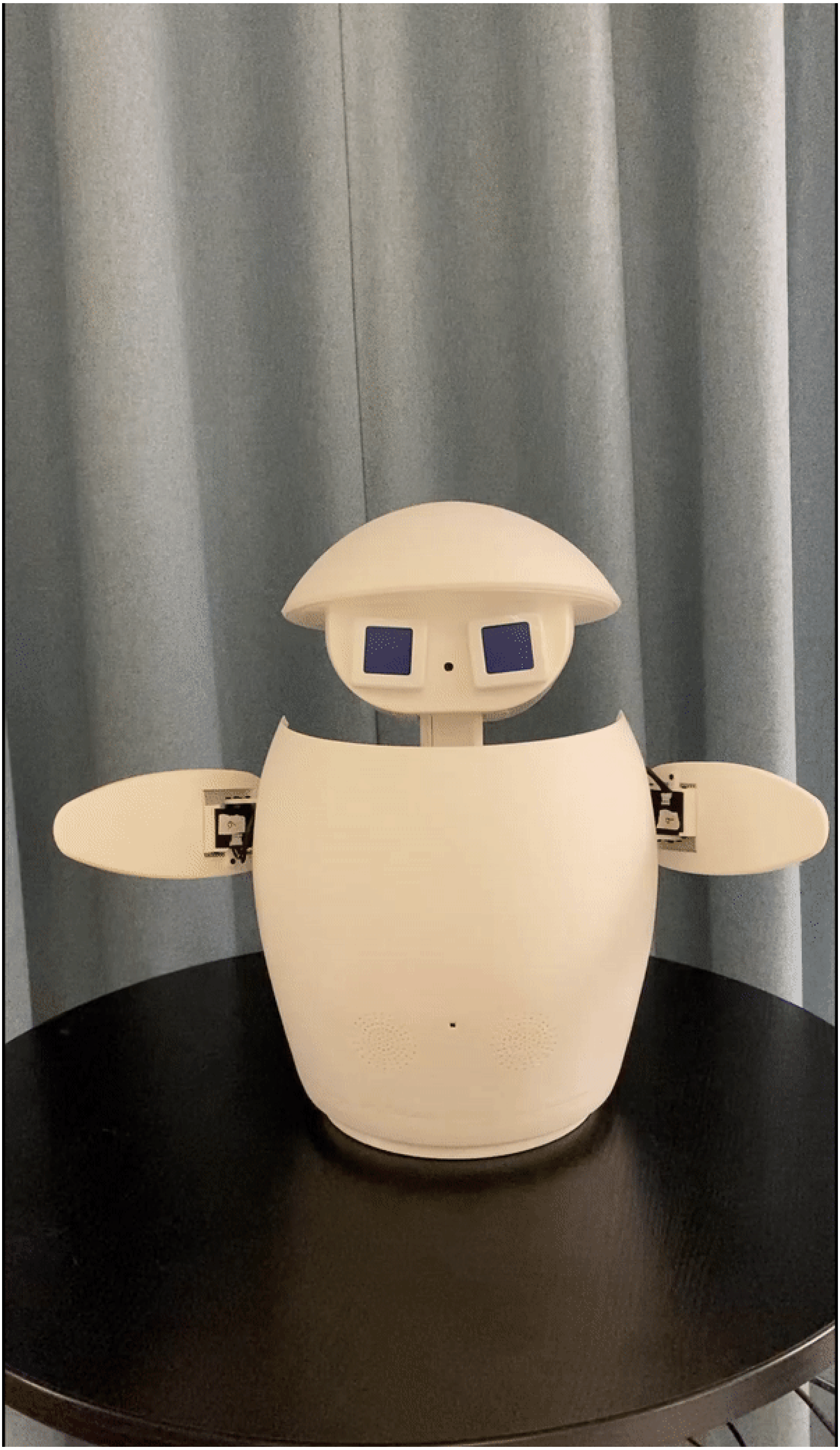


11. Which emotion do you associate with video nr 2?

Markera endast en oval.

- Happy
- Sad
- Angry
- Disgust
- Surprised
- Shy

Video nr 2

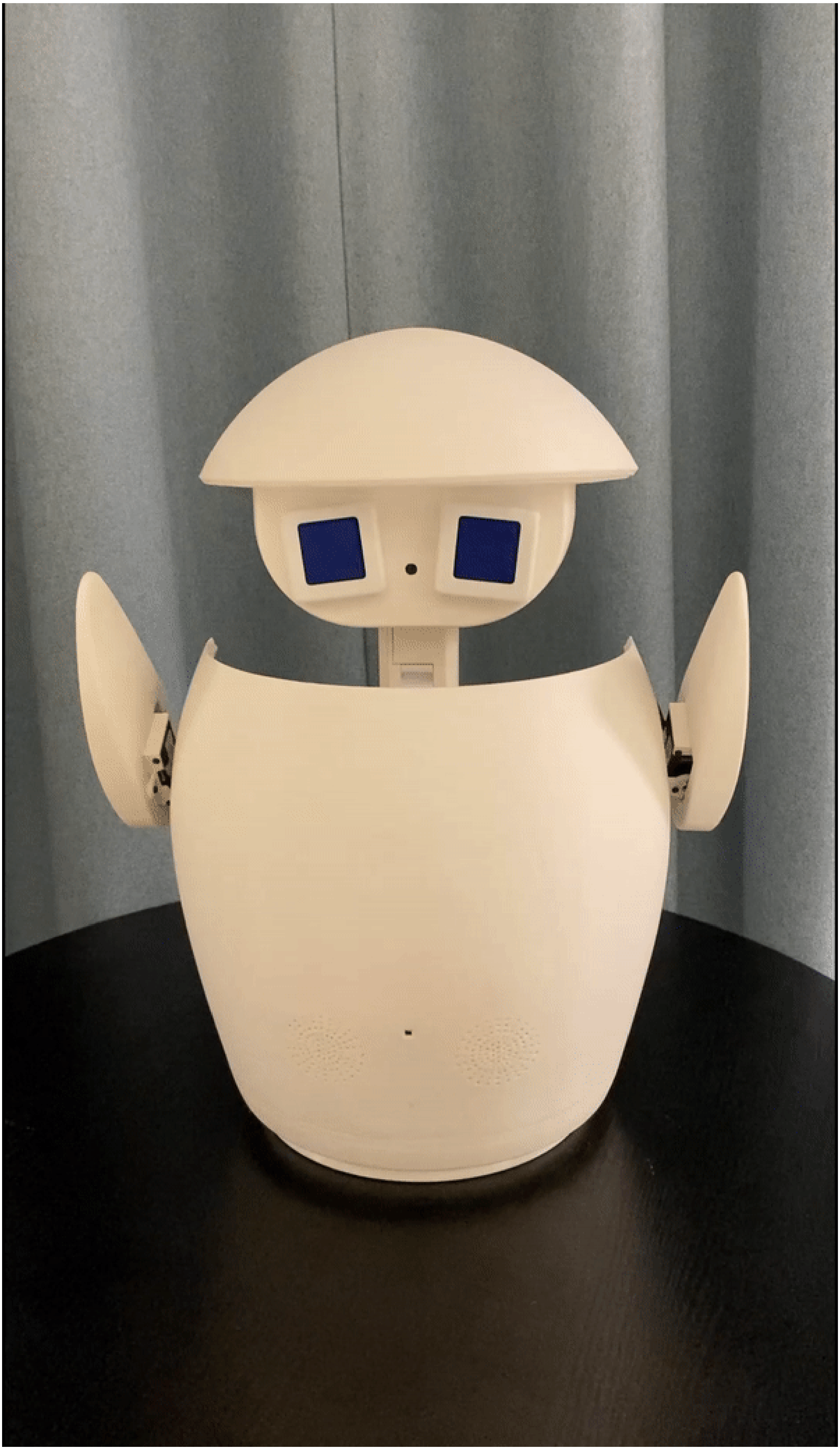


12. Which emotion do you associate with video nr 3?

Markera endast en oval.

- Happy
- Sad
- Angry
- Disgust
- Surprised
- Shy

Video nr 3



13. Which emotion do you associate with video nr 4?

Markera endast en oval.

- Happy
- Sad
- Angry
- Disgust
- Surprised
- Shy

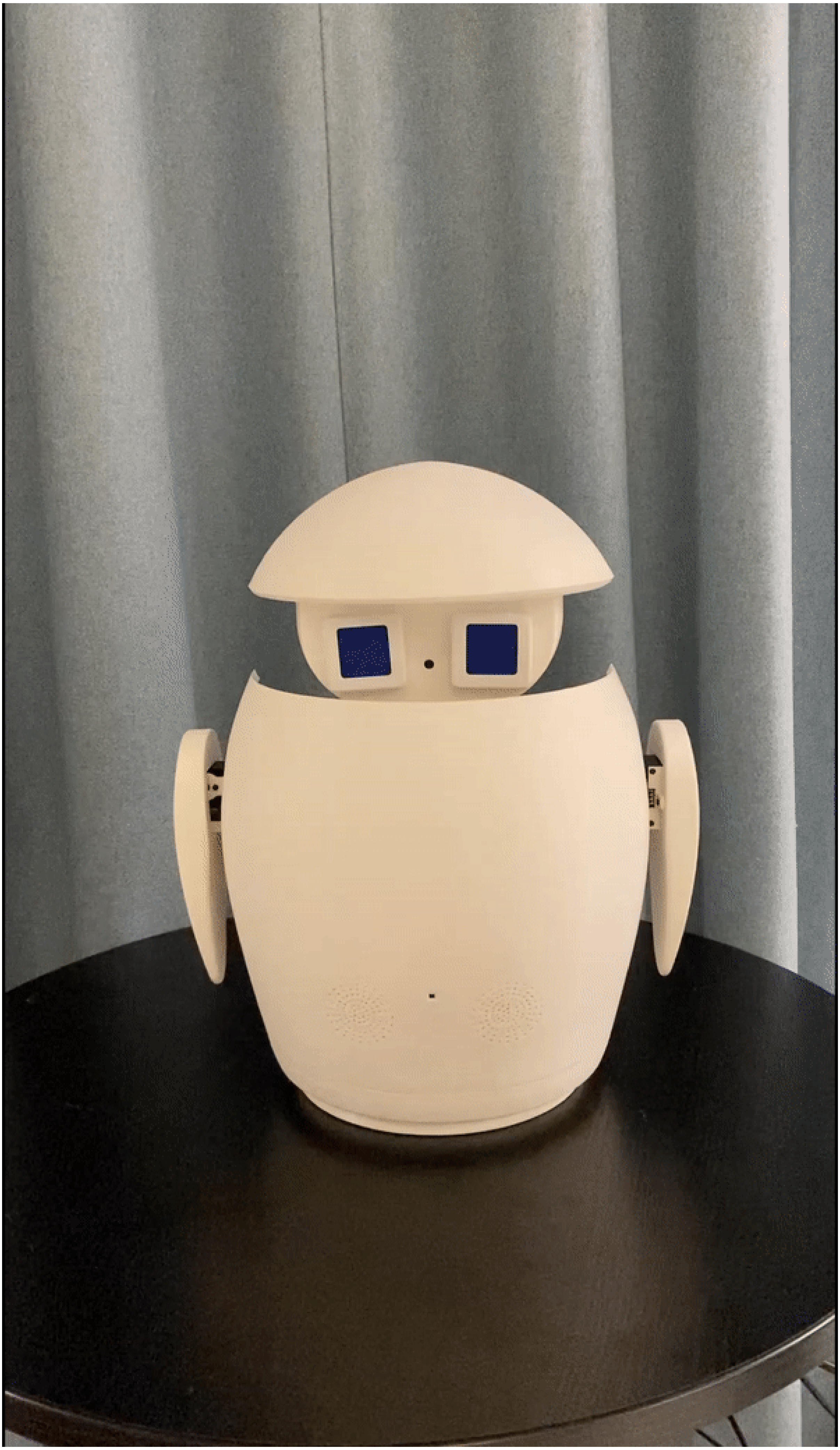
Video nr 4

14. Which emotion do you associate with video nr 5?

Markera endast en oval.

- Happy
- Sad
- Angry
- Disgust
- Surprised
- Shy

Video nr 5

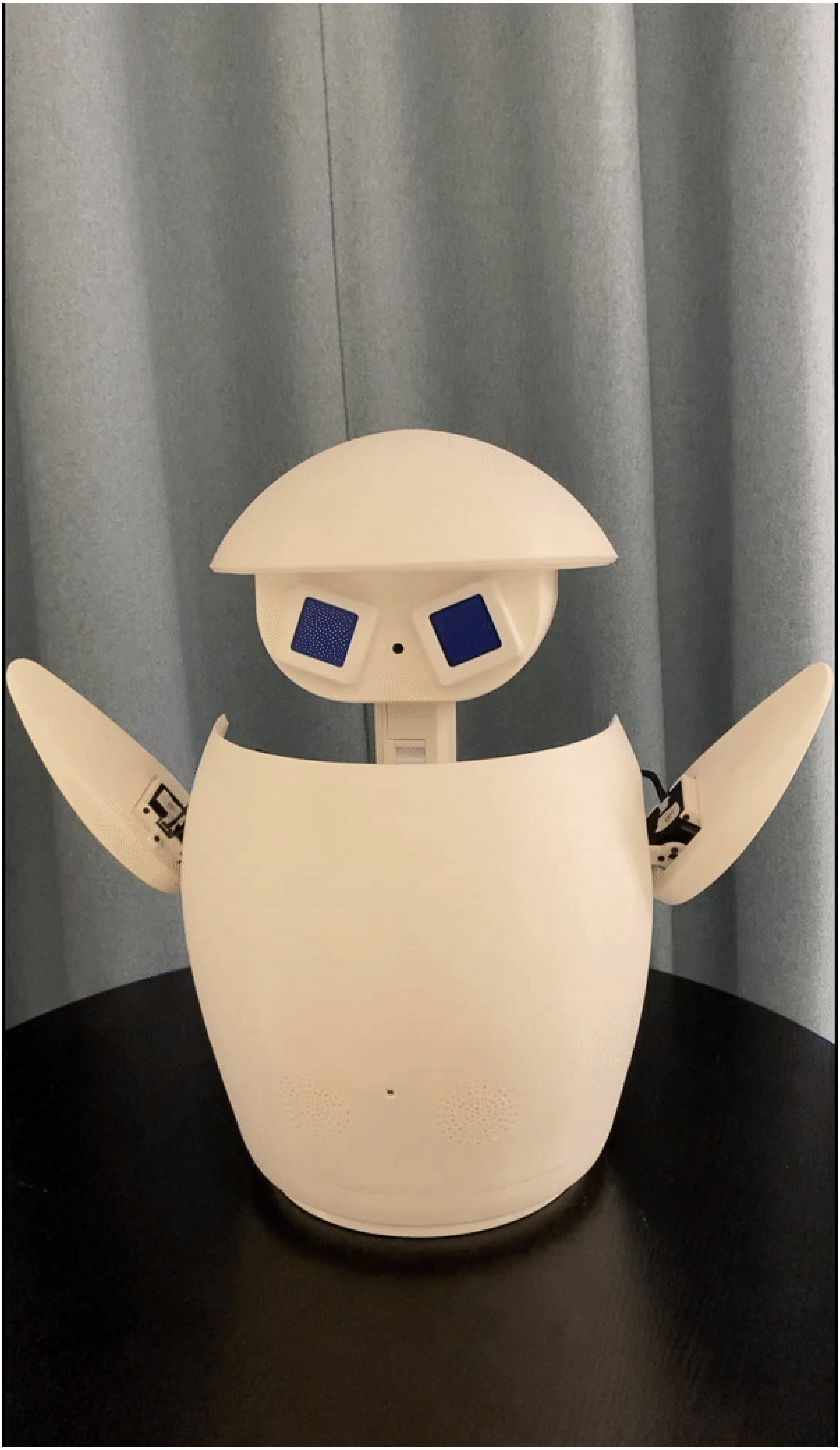


15. Which emotion do you associate with video nr 6?

Markera endast en oval.

- Happy
- Sad
- Angry
- Disgust
- Surprised
- Shy

Video nr 6



H.2.1 Questionnaire 2, Age result

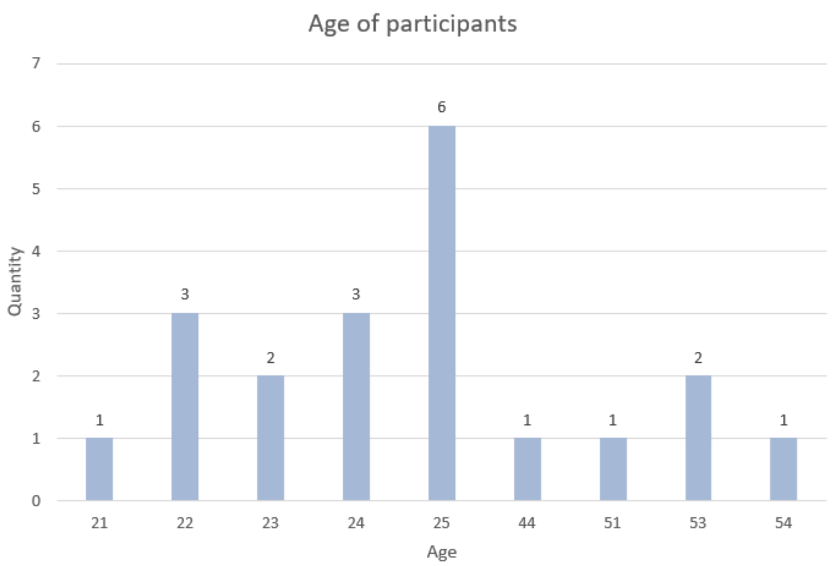


Figure H.4. *A bar-chart showing the age of the 21 participants. Bar-chart made in Excel.*

H.2.2 Questionnaire 2, Country result

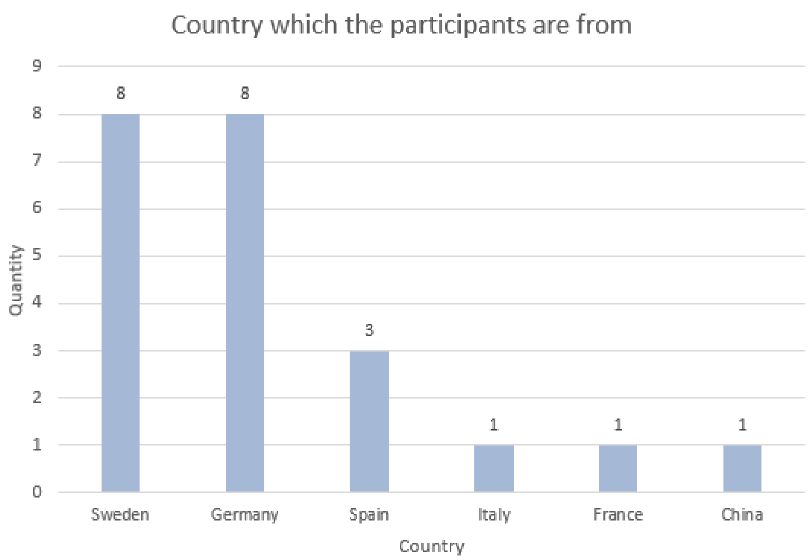


Figure H.5. *A bar-chart showing which country the 21 participants came from. Bar-chart made in Excel.*

H.2.3 Questionnaire 2, Seen the final presentation

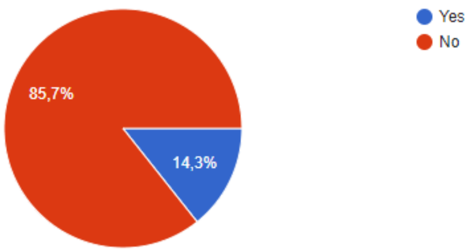


Figure H.6. A pie-chart showing how many of the participants had seen the final presentation. Pie-chart made in Excel.