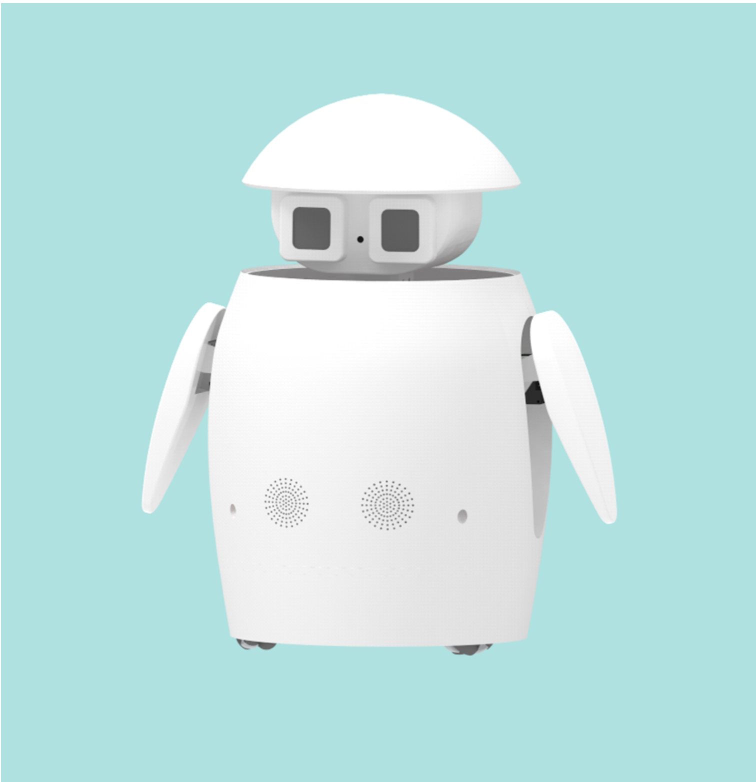
Agåker Karlsson, Agnes	agnak@kth.se
Deng, Shuyi	shuyid@kth.se
Johansson, David	djoh6@kth.se
Jönsson, Iris	irisj@kth.se
Kou, Mingcheng	minkou@kth.se
Löfgren, Felix	felixlo@kth.se
Pekola, Tobias	tpekola@kth.se
Ragnarsson, Geir	geirr@kth.se
Sundqvist, Sigge	siggesu@kth.se

Sunday 15th December, 2024

MF2058 Mechatronics, Advanced Course Fall Semester

AKI



Abstract

The project is a continuation of a previous project that was part of the Mechatronics Higher course - Högre kurs (HK) in 2022. The goal was to create AKI, a social robot that would be able to express six basic emotions: happiness, sadness, surprise, fear, anger, and disgust.

The goal of this project is to revise and expand AKI's mechatronic design, extending its functionalities while ensuring reliable operation over an extended period of time. The robot shall have locomotion capabilities, updated structural design, response to ledges and obstacles, verbal communication, and wireless operation. It should do this while fulfilling the part of UNICEF policy guidelines on AI for children.

This report includes the SOTA for each of the robots' functionalities: existing solutions, locomotions, patterns and emotions, obstacle detection, reliability, verbal communication, hardware, and wireless operation. From the SOTA, a concept design was made. The type of locomotion that was chosen was omni wheels, primarily because of its maneuverability. It also includes locomotion patterns that was implemented, corresponding to one of six basic emotions. ToF sensors were chosen to support AKI's movement by detecting the environment and surrounding obstacles. The wireless operation has also been primarily designed as a LiPON battery providing power, and Wi-Fi was chosen for communication. For verbal communication, prerecorded audio for each of the six emotions was made.

The final robot was able to express its emotions while moving in a predefined pattern. Additionally, the robot featured obstacle detection, which was verified to work for both edges and obstacles. Furthermore, it was equipped to operate wirelessly and send and receive data. A significant part of this project was to improve the robot's reliability through better design and higher-quality components. Several improvements were made to increase the robot's reliability. Some of the changes included integrating more modular programs for easier testing and debugging, using threaded inserts for stronger assembly, and an updated interior design for improved functionality. Future improvements could include integrating AI for more advanced user interaction and communication, implementing position control for precise locomotion, and adding a wireless emergency stop (E-stop) for better safety.

This project's stakeholder is Georgios Andrikopoulos, the professor of the Robot Design Lab of the Mechatronics Unit. The work is done with support from the HONDA Research Institute of Japan.

Acknowledgements

We would like to express our sincere gratitude to the Honda Research Institute of Japan and our stakeholder, Georgios Andrikopoulos, for providing the opportunity to develop this project. We also extend our heartfelt thanks to our supervisors, Seshagopalan Thorapalli Muralidharan, Björn Möller, Jad El-Khoury and Daniel Frede for their dedication and assistance during the project. This report would not have been possible without their invaluable support and guidance throughout the process. Additionally, we are grateful to the previous HK team for their significant contributions to the development of the prototype, which laid the foundation for our work. Finally, we would like to thank Johannes Toma for his help with 3D printing and for assisting with the refinement of various components.

Contents

List of Figures

Acronyms

AI Artificial Intelligence

ASTM American Society for Testing and Materials

CAD Computer Aided Design

CPU Central Processing Unit

DoF Degrees of Freedom

FMEA Failure Mode Effect Analysis

HK Higher course - Högre kurs

HD High Definition

HRI Human-Robot Interaction

IR Infrared

KTH KTH - Royal Institute of Technology

LCD Liquid Crystal Display

LiPON Lithium Phosphorus Oxynitride

NiMH Nickel-Metal Hydride

NiOOH Nickel Oxide Hydroxide

OpenCV Open Source Computer Vision Library

SIM Subscriber Identity Module

SOTA State Of The Art

ToF Time of Flight

UWB Ultra Wide Band

1 Introduction

This section provides an overview of the project's background, scope, team structure, requirements, and ethical considerations.

1.1 Background

This project is a further development of an existing robot called Fuyu. The original robot is a social tabletop robot from a research project from KTH - Royal Institute of Technology (KTH), Stockholm, Sweden [6]. In this report, this version is referred to as "the old AKI".

The interaction between humans and robots has become more lifelike and sophisticated over the years. Robots designed for different purposes, for example, in service and hospitality, are increasingly capable of assisting humans in their daily lives. One sector where robots are currently being introduced and researched is in schools and classrooms, where they can serve as tools for teachers and aids for students [7]. Social robots have also been shown to help the development of social communication skills in children and adolescents with autism [8].

To effectively engage children, the robot needs to have a variety of human-like features. Adding and developing functions for robots is costly, so these features need to provide significant added value to the interactions. Choosing the right functions is crucial to balancing the robot's cost efficiency and effectiveness.

The field of Human-Robot Interaction (HRI) is a relatively young field that outlines some key concepts for enhancing the user experience when interacting with a robot. The robot needs to be seen as a living entity with its own goals and achievements, where interactions with humans fulfill the robot's needs. Also, its behavior and manners must be acceptable and comfortable to humans, while its actions and decisions need to be seen as intelligent and intentional [9]. These human-like characteristics must permeate the robot's features and attributes to get a satisfactory user experience.

1.2 Scope

This project aims to build a new robot, AKI, based on the foundation of the previous robot, Fuyu, in order to enhance the user experience during interactions. It is an open-ended project from KTH, where the team is asked to collaborate and develop solutions to fulfill the stakeholder's requirements. The project aims to advance the team's proficiency in mechatronics further and spans over two semesters. During the first one, research and concept development was undertaken. During the second semester, the focus was to build and develop new features for the robot.

The team created and developed the project's requirements in compliance with UNICEF policy guidance on AI for children. Stakeholder Georgios Andrikopoulos later verified and confirmed them.

1.3 Team Structure and Management

The team consists of nine members with the same responsibilities to contribute to the project. Before the team started any work, a code of conduct was created that every member contributed to and signed. The contract stated the team's rules and the penalties for breaking them. For instance, one rule stated that every individual is expected to deliver at least 400 working hours in the fall semester, corresponding to the course's 18 credits.

The team has split into smaller subteams that have focus on different implementations of AKI. Those teams were flexible. This means that the size of those subteams will differ depending on the workload of that task. Also, the group members will change tasks and subteams regularly during the semester to ensure that every member will have worked on multiple tasks related to the work.

That way, it can be ensured that all members will have worked on the tasks related to software, electronics, mechanics, and control, which are the branches on which mechatronics focuses.

The team has shared responsibilities. Someone takes notes during meetings, and one or two project managers ensure that everyone in the group is involved and that the project deadline is met. These responsibilities are shifted during the project from one team member to another.

1.4 Requirements

Below are the stakeholder requirements:

Must-Have Requirements:

1. Enabling Wheeled Locomotion
    - Enabling wheeled locomotion of the robot platform in at least 2 Degrees of Freedom (DoF).
    - The locomotion shall enhance mobility or the addition of mobility, which creates the potential for greater expressivity.
2. Ensuring Operational Reliability
    - Implementation of rigid components to increase reliability and presentation quality.
    - Achieve motion control reliability over extended periods of operation.
    - Ensure locomotion noise levels are within permissible ranges for children-robot interaction.
    - Ensuring the component's temperature level is stable and in an acceptable range under prolonged operation.
    - The program code must be modular, facilitating easy testing, and be validated to ensure seamless operation for extended periods without unexpected behaviors.
3. The robot ensures safe usage for children by complying with UNICEF's requirements 3 & 6.
    - Prioritize fairness and non-discrimination for children.
    - Provide transparency, explainability, and accountability for children.
4. The robot shall be able to operate wireless.
5. The robot shall detect obstacles and avoid them.

Nice-to-Have Requirements:

1. Enabling Wireless Operation and Communication
    - Should be able to get data in and out of the robot wirelessly.
2. The robot should be able to speak

Technical requirements were made based on the stakeholder's requirements. They were made to specify the needs of the final product further. These requirements can be found in Appendix B.

1.5 Ethics and Risks

Social robotics has a significant impact on healthcare and plays an essential role in providing companionship for children. To comply with the UNICEF goals, considerations regarding privacy, the ethical role of robots, and their effects on children are crucial and must be addressed in this project. To deal with that, a limited scope of topics will be implemented, and the emotional expression of the robot will be carefully designed based on current psychological research to prevent any negative impact on children. In addition, the possibility of malfunction must be analyzed and handled.

Internal risks were evaluated using a Failure Mode Analysis Failure Mode Effect Analysis (FMEA). This approach aimed to increase awareness of potential issues and provide actionable proposals to address problems that might arise during the project. For more details, see Appendix D.

2 State of The Art

This State Of The Art (SOTA) chapter provides a overview of the current advancements and methodologies in social robotics for kids. AKI was divided into individual processes that needed to be completed independently before being combined into the final product. Those processes consisted of a few key concepts. Those concepts were researched and presented below.

2.1 Existing Solutions

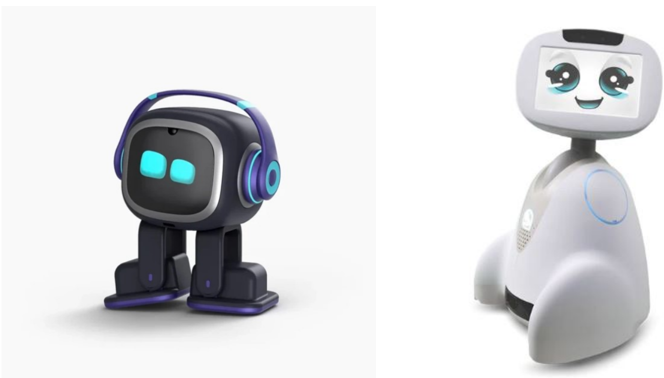
This section analyzes two existing interactive robot products.

2.1.1 EMO

EMO is an Artificial Intelligence (AI) desktop robot pet developed by Living.AI. EMO's facial expression is performed by a screen on his head, generally showing his "eyes". For better human-like interaction, it equips various actuators and sensors. With bipedal legs, it can move around the desk. The High Definition (HD) camera can recognize the user. For verbal communication, the mic array and speaker are used for listening and speaking. It also has optical drop sensors to avoid dropping down from the desk. To make it more like a friend rather than just a toy, a built-in development system is applied to allow its skills to increase as it "grows up" [10]. EMO can be seen in Figure 1a.

2.1.2 Buddy

Buddy from Blue Frog Robotics is a companion robot that can interact with the user through vision, touch, or voice. Similarly to AKI, it can also show facial emotions. However, one big difference is the wheels, which allow Buddy to move by rolling, and it can also avoid some obstacles with the help of multiple obstacle sensors. Other types of sensors it has are cliff sensors, cameras, caress sensors, omnidirectional microphones, a touch screen, and actuators (wheel motors, head motors, arm connectors). The voice interaction is done through pre-learned commands and actions. For instance, if the user says, "Can you dance?" the robot will dance a little bit, and "Go for a walk" will make Buddy go for a random walk. Buddy can move in 4 degrees of freedom and has differential drive as a type of locomotion. It communicates via WiFi wireless networks, a 4G Subscriber Identity Module (SIM) card (optional), and Bluetooth. Recharging is achieved manually through a connector plugged into the charger or autonomously by returning to its charging station (optional) [11]. Buddy can be seen in Figure 1b



(a) EMO [10] (b) Buddy [11]

Figure 1: Existing solutions

2.2 Locomotion

This project's key stakeholder requirement and focal point is to develop a locomotion system for AKI. Additionally, stakeholders have specifically requested a wheeled locomotion system with low-profile wheels. Therefore, this section of the SOTA analysis delves into research aspects concerning locomotion, including locomotion and human-robot interaction (HRI), as well as exploring various types of locomotion.

2.2.1 Locomotion and Human-Robot Interaction

In recent years, locomotion capability has become an essential part of HRI. Many studies demonstrated that interactive robots with locomotion functionality can achieve better HRI effects.

H. Huettenrauch's research drew on some research results on social distance in interpersonal relationships and found that interactive robots should dynamically adjust the positional relationship with users to maintain a good interactive environment [12]. Ono et al.[13] finds that locomotion and other movements of an interactive robot can improve the understanding of utterance by enabling the construction of a triadic relationship among individuals, objects, and the environment, which facilitates communication and comprehension. Research by Elie et al. shows that by combining waving, greeting, and moving toward the target, interactive robots can more effectively attract the target's attention [14].

Therefore, locomotion is introduced into many mainstream experiments of interactive robots. For instance, an experiment conducted by CMU designed a robot receptionist with a moving base and a pan-tilt unit to keep tracking the person to whom it is talking [15]. Another one was Kanda's experiment, which designed a humanoid robot, Robovie, for socializing with children, which has a two-wheel moving base for locomotion [16]. In Kishi's research, the third one was a humanoid robot, KOBIAN, designed for comedy performances. KOBIAN has a bipedal unit to achieve locomotion and perform necessary body language to make the audience laugh [17].

2.2.2 Types of Locomotion

There are multiple ways to design locomotion for a robot, and different types have different benefits and drawbacks. Therefore, when deciding on a locomotion type, the designer must consider the robot's application, purpose, and requirements. In this case, the main objective is to add locomotion for movement indoors, which means flat terrain but possibly narrow and small moving areas. Below are various types of locomotion (mostly wheeled) introduced to give the designers different options to choose what best suits them.

- **Omni Wheels**: Omni wheels enable movement in the direction the wheel is pointing and perpendicular to it. Arranging three wheels in a structure makes various types of movement possible. For example, the structure can move sideways without needing to turn in that direction [18]. An omni wheel can be seen in Figure 2.
- **Mecanum Wheels**: Similar to omni wheels, but with rollers set at an angle to the rotational axis of the wheel. This allows the robot to rotate and move in any direction, offering great agility. This type of locomotion is common for movement in narrow spaces, often used inside warehouses on forklifts [19]. AMecanuum wheels can be seen in Figure 2b.

(a) Omni wheel [18]

(b) Mecanum wheels [19]

Figure 2: Omni wheels and Mecanum wheels

- **Differential Drive**: Differential drive employs two wheels, each driven by its own motor. By independently adjusting the speed of each wheel, the robot can turn. There are various configurations of differential drive systems. One basic configuration involves using only the two main wheels, see Figure 3a, necessitating some form of balancing control to prevent the robot from tipping over. The most prevalent setup includes adding a caster wheel or rolling ball, which introduces a third point of contact, see Figure 3b [1]. Differential drive is a simple concept that does not require excessive calculations and control while still allowing flexible movement on flat terrain.

(a) Differential drive configuration

(b) Caster wheel/rolling ball configuration

Figure 3: Differential drive configurations [1]

- **Swerve Drive**: A system in which each wheel can point in any direction. Since the wheels can point in any direction, the robot can move in any direction. This allows for both translation and rotation without the need for differential steering. Additionally, it can maneuver very well in tight spaces since it can turn its wheels to form a circle and spin, this can be seen in Figure 4. This type of locomotion would, however, require additional motors and power[2].

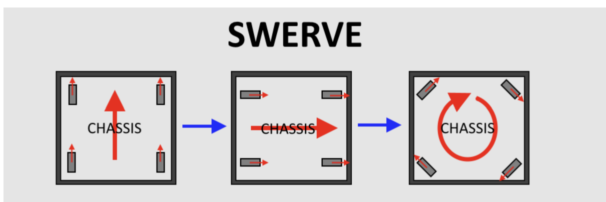
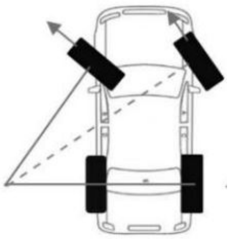


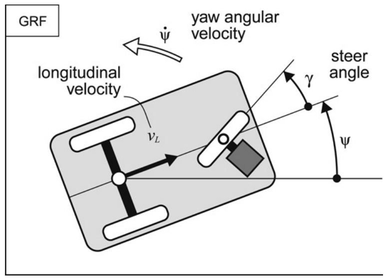
Figure 4: Movement of a robot with a swerve drive [2]

- **Ackerman steering**: Like a car that has 4 wheels. The two front wheels handle the steering while the rear 2 are stable, see Figure 5a This is however not very maneuverable in tight spaces [20].

- **Tricycle Drive**: Two driven rear wheels and one steerable front wheel. Not very maneuverable in tight spaces. Even though it looks similar to differential drive, it is more comparable to Ackerman steering, since the two driven rear wheels will always have the same speed, and the turning will be handled by the front steering, see Figure 5.



(a) Ackerman steering [20]



(b) Mobile robot with tricycle kinematics [21]

Figure 5: Ackerman Steering and Tricycle Drive

- **Synchro Drive**: All wheels are steered together and driven simultaneously, see Figure 6. That means it is very good for maneuvering in tight spaces, but the bad thing is that it always faces the same direction.

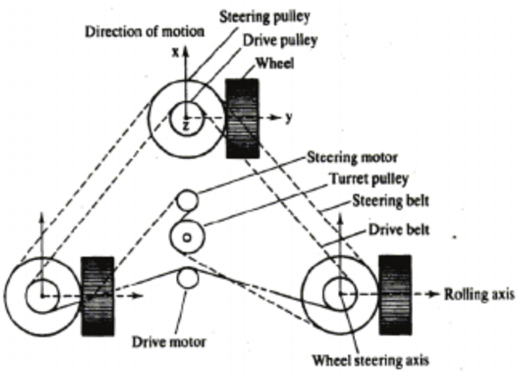


Figure 6: Synchro drive

- **Explicit Steering**: In explicit steering, the chassis is not fixed; the wheels can turn freely. It is accomplished by changing the heading of the wheels to cause a change in the vehicle's heading. [3]. Explicit steering can be seen to the left of Figure 7.
- **Skid Steering**: The chassis is fixed, so the wheels always look straight ahead. The Wheels on each side are synchronized in movement, so the robot can only make turns if the wheels spin at different speeds on each side. This is good for movement in tight spaces [3]. Skid steering can be seen to the right of Figure 7.

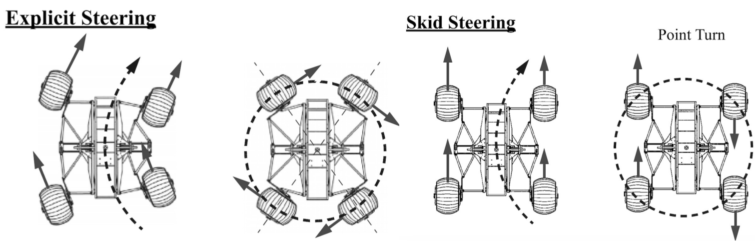


Figure 7: Explicit steering compared to skid steering [3]

- **Statically unstable two wheels**: Uses two coaxial wheels and has the center of the body above the wheel axle. It uses an inverted pendulum model to actively stabilize. It will topple over if it is not actively stabilizing [22].
- **Legs**: Legged robots can step over objects. They involve more complexity, have more degrees of freedom compared to wheeled locomotion, and are less energy efficient [22].

2.3 Patterns and emotions

Body movement is a standout feature that distinguishes robots from other machines. It serves as a powerful medium for expressing emotions and intentions. When humans interact with robots, they tend to be psychologically affected by the robot's movement. That is why the robot has to display the correct emotion and intention, which reflect the condition of its system and the context of its interaction with the human, for example.

Nonverbal communication is a prevalent form of human interaction that involves conveying messages without spoken words. Humans have a strong tendency to sense and be cued by the movements of other people and objects. Also, humans have a tendency to personify non-human machines and objects. As a result, robots working close to humans are strong determinants to produce psychological effects on him or her [23].

Furthermore, displaying motion to complement facial expressions has showed to increase the recognition of the emotion. One study with a robot showed that there was an average increase of +33.5 % compared to simple facial expression recognition, with particularly notable increases observed for Anger (+61.7 %) and Surprise (+68.5 %) [24].

2.3.1 Happiness

There are many parts of the movement that contribute to a happy emotion. The most associated with happiness are jump, spread, rhythmicity, free and light, up and rise, and rotation. The rhythmic movement is distinct but involves moving or dancing in a specific rhythm. The spreading movement is also very characteristic, but it involves spreading the arms and reaching out. Those two movements are the ones that increase the ability to recognize happiness the most [25].

2.3.2 Sad

There are also nonverbal communications that contribute to being sad. Some body gestures are lowering the head and keeping eyes open or closed. Another gesture is to have a hunched back, which creates a closed body language position.

The movements that contribute to being sad are slow body movements; for example, a sad person looks like they are dragging their feet when they walk. It also has swallowing movements, which occur in a sad person's neck area, indicating that that person may be about to cry. The last movement related to being sad is because a sad person is so focused inward, making it more likely to be tripping over things [26].

2.3.3 Anger

The components of movement that most notably are connected to anger are strong, sudden, advanced, and direct. Sudden is the component that most increase the recognition of anger, it increases the recognition of anger by over 9 times [25].

2.3.4 Disgusted

There are a few components of movement that contribute to the feeling of disgust. The most notable expressions of feeling disgust and contempt are facial expressions, not movements. But still, the movement of disgust is to move to the side, facing away from the things that disgust us [27].

2.3.5 Surprised

The movement of surprise is the quickest of all the other emotions because that feeling only lasts for a couple of seconds. The movement that is connected to surprise is to take one short step back from the surprising element [28].

2.3.6 Fear

The components of movement that express fear include movements such as bind, retreat, condense and enclose, and twist and back, with the most significant expressions being retreat and twist and back [25].

2.4 Obstacle Detection

In this project, AKI is expected to avoid potential obstacles during operation. Considering our application is primarily indoor and involves usage on the table with edges, the focus is on addressing ledges and obstacles the robot may encounter during movement to ensure it can navigate around obstacles along its path and recognize edges to prevent the robot from falling. The selection of appropriate sensors to meet these requirements is explored in detail.

- **Infrared (IR) Sensor**: An IR sensor is an electronic device that emits infrared radiation to sense some aspects of the surroundings, how it works can be seen in Figure 8. It offers simplicity in implementation, reduced power consumption, and excels in detecting objects in low-light conditions. However, their detection angle is limited. Additionally, since IR sensors depend on temperature differentials for detection, detecting objects with similar temperatures to the background would be a challenge [29].

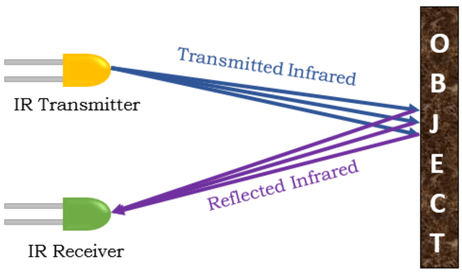


Figure 8: IR sensor [4]

- **Cliff Sensor**: Cliff sensor is mainly used in robotic vacuum cleaners to help prevent them from falling off edges or stairs. These sensors use infrared technology to detect changes in floor height and alert the vacuum cleaner to change its direction or avoid the obstacle altogether. This ensures that the vacuum cleaner operates safely and efficiently without the risk of damage or accidents [30].
- **LiDAR**: LiDAR works by sending out pulses of (usually infrared) light in a tight beam to a distant object, then measuring the time it takes for the reflected light to return, which is widely used in autonomous driving applications. LiDAR has various strengths: a large field of view, power efficiency, speed, and robustness. Despite that, LiDAR is not without limitations. Its performance is easily affected by environmental factors. On the other hand, LiDAR is a complex device with rotating parts, usually expensive and susceptible to mechanical damage [31].

- **Stereo Camera**: Stereo cameras, unaffected by light emission and capable of functioning in various lighting conditions, are suitable for indoor and outdoor use due to their robustness. Compared to other active sensors, it has a simple structure and is far less expensive. Moreover, it has the inherent ability to extract a high-quality color image well-aligned to the depth map. Overall, a stereo camera is an excellent choice for robot navigation and mapping in diverse, unstructured environments [32].
- **Monocular Camera**: Monocular camera is a versatile imaging device that plays a crucial role in capturing visual information. Its compact size, cost-effectiveness, and ability to capture high-resolution images make it a popular choice in various industries. With advancements in computer vision and machine learning, monocular cameras are becoming even more powerful in their ability to understand and interpret the visual world. Unlike a stereo camera that uses two lenses to create a 3D effect, a monocular camera captures images in 2D [33].
- **Time of Flight (ToF) Camera**: All ToF cameras are compact, lightweight, and relatively inexpensive, making them suitable for embedding in small devices such as cell phones. They operate effectively in low light conditions or darkness due to their own laser illumination. Their accuracy rivals that of Structured Light Cameras, ranging from 1mm to 1cm. Indirect ToF cameras offer high-resolution depth information up to 640×480 pixels. With rapid operation at up to 60 frames per second, ToF cameras are ideal for real-time applications. Moreover, ToF cameras are cost-effective compared to alternatives like Structured Light Cameras and LiDAR sensors [34].

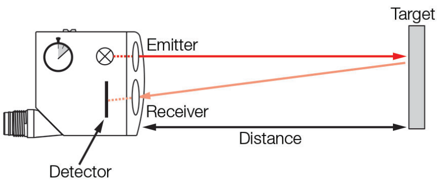


Figure 9: ToF Camera [5]

2.5 Reliability

Currently, Fuyu has been equipped with a complete system. It can achieve basic emotional expressions while movable auxiliary arms and head are implemented for communication with users. The robot utilizes Open Source Computer Vision Library (OpenCV) for person-tracking its surroundings and can greet users upon initial interaction. Additionally, the speaker is available but not extensively utilized for user interaction. However, AKI experiences mechanical system friction and motor overloading, leading to noise and temperature concerns. Additionally, Arduino Nano disconnections occur during operation. On another note, the mechanical structure design requires improvement, as disassembling the robot becomes challenging once all parts are screwed in place and when all electronics are connected [6].

In order for the robot to maintain stable and consistent performance for a prolonged period of time, the robustness of its components is paramount. The robot's robustness criteria can be dissected into four categories involving its mechanical, electrical, and software components, with an additional thermal section to ensure reliable operations over long-hour usage.

2.5.1 Mechanical

Mechanical wear can break or render the robot's components less effective. The American Society for Testing and Materials (ASTM) Committee categorizes mechanical wear into abrasive and nonabrasive. Abrasive wear occurs when a hard surface slides along a softer surface. The result can be compromised or distorted components. Nonabrasive wear typically occurs in sliding systems with materials of similar hardness, for example, roll bearing and gears [35].

Friction between moving surfaces is the primary reason for failure in machines, influenced by factors such as load, speed, hardness, and roughness of the surface of the two sliding pairs [36].

To minimize abrasive and nonabrasive wear, reducing friction can significantly impact the robot's robustness. Additional measures that can be taken are creating smooth surfaces and reducing load.

Regarding the noise issue, the gear rack structures in the neck exhibit higher noise levels. On one hand, despite sanding, the 3D printed materials currently in use remain relatively rough, which is an area for potential improvement. On the other hand, as mentioned in previous test reports, it is better to redesign the slider, even if lubrication resolves it in the short term [6]. A thing to consider is implementing structures with lower friction to address direct friction between materials in the original design, such as by incorporating bearings. Additionally, inspection and maintenance issues for the robot should be considered when redesigning the mechanical structure. This implies that the robot should be designed to assemble and disassemble individual components easily.

2.5.2 Electrical

Wiring optimization is needed because there were periodic disconnections with the Arduino Nano during experiments. Firstly, choose appropriate electrical control components and controllers to ensure the reliability and stability of the system, considering the component's size, load capacity, and working noise. Secondly, the system layout and wiring of the electrical system should be designed according to the robot's motion trajectory and sensor positions to avoid electromagnetic interference and power supply noise, as well as the disconnection error that occurs during operation. In addition, meeting fundamental electrical system safety requirements and implementing appropriate electrical safety measures such as isolation switches, fuses, and grounding are necessary to ensure the safety of the robot's electrical system. Besides, an emergency switch is significant to ensure safety during robot operation.

2.5.3 Software

The existing software is built on C++, operating with a master from a UP Core and two slaves, Arduino Nano and Teensy 4.0. It is currently compatible with Ubuntu 22.04 and is modularized as a distributed system, with each slave and master responsible for various operations. The programming is structured to execute all operations sequentially from a unified C file. The stakeholder's objective is to redesign the program to improve it and create faster sampling. One approach to achieve this could involve modularization of the software using threads, semaphores, etc, possibly adding more Central Processing Unit (CPU)'s to increase speed and computational power.

2.5.4 Thermal

The thermal part can be part of the mechanical, electrical, and software since overheating is mainly caused by overload due to unreasonable mechanical design, unsuitable electrical components, and excessive demands on computation (software). In the current state, thermal is not of concern but needs to be considered when adding electrical components. One way to solve the problem would be heat-dissipating components such as a fan and thermal interface material (silicon thermal pad) for the robot mainboard.

2.6 Wireless Operation

For tabletop robots, wireless operation provides flexibility and a cleaner look. To enable wireless operation, battery is needed for powering the robot without a power cable, wireless communication achieves controlling the robot and transmitting data wirelessly.

2.6.1 Battery

To enable robust wireless operation, the robot should have an independent power source. Batteries are a way to power a desktop robot. This section studies several commonly used battery technologies.

- Alkaline batteries: A type of primary battery that is usually made of zinc as anode and manganese dioxide as cathode with an alkaline electrolyte. Alkaline batteries offer high energy density and long shelf-life, which makes them very popular in cheap small electrical appliances and toys. However, because they are disposable, alkaline batteries will create harmful waste with hazardous substances and have higher costs than rechargeable batteries in the long run.
- Nickel-Metal Hydride (NiMH) batteries: A type of rechargeable battery consists of a hydrogen-absorbing alloy for the anode and a Nickel Oxide Hydroxide (NiOOH) for the cathode. The electrolyte used is usually potassium hydroxide. NiMH battery is currently the least expensive rechargeable battery technology [37], and it is environmentally friendly since lacking toxic heavy metals compared with other solutions.
- Lithium-Ion batteries: The most popular type of rechargeable battery used in portable electronic devices commonly consists of a graphite anode and lithium metal oxide. Compared with NiMH batteries, Li-Ion batteries often have higher energy density and more cycle life. At the same time, higher voltage also makes Li-Ion batteries have broader application scenarios [38]. Different cathode materials provide different performances. For small robots, Lithium Phosphorus Oxynitride (LiPON) is the predominant choice [39].

2.6.2 Wireless Communication

When considering the need for a robot to freely move indoors and communicate wirelessly with a control terminal, selecting a technology suitable for short-range communication is crucial. Based on AKI's application scenario, research was primarily focused on the following four short-range wireless communication technologies.

- **Ultra Wide Band (UWB)**: UWB is a wireless technology that uses very low energy pulses of radio waves to transmit data and measure the location and direction of objects with high accuracy [40].
- **Wi-Fi**: Wi-Fi is a technology that enables electronic devices to connect to local networks through radio waves [41]. Wi-Fi has been widely applied, it boasts stability and supports connectivity with a variety of devices. For wireless communication needs in robotics applications, Wi-Fi effectively meets the demands of wireless communication in robotics, facilitating real-time transmission of extensive data, including sensor data.
- **Bluetooth**: Bluetooth devices send short-range radio signals to connect with each other, replacing the need for cable connections. They consist of transceivers, basebands, and protocol stacks, enabling the formation of small or large networks [40].
- **ZigBee**: Zigbee, introduced in 2003, aimed to overcome Bluetooth's limitations like complexity, high power usage, limited range, and small network scalability. Zigbee uses self-organizing network communication and is a leading wireless protocol in sensor networks [42].

3 Methodology

This project encompasses various mechatronic challenges that require diverse engineering approaches for effective solutions. Each area of the project demands specific tools, methods, and techniques tailored to its unique needs. Additionally, the selection of appropriate software development tools and the implementation of efficient project management strategies are critical to ensuring the project's success. This chapter presents the methodology used to address these challenges, outlining the tools, techniques, and processes employed throughout the project.

3.1 Concept Design

Most of the design was kept from the previous Fuyu robot. However, some new features, like the locomotion type, obstacle detection technology, and power supply, were decided based on decision matrices by assigning weights to various evaluation factors; these can be seen in Appendix A.

3.2 Design Process

The design process for AKI was divided into four main subsystems: the head, the arms, the neck, and the locomotion module. This clear partitioning enabled effective parallel work, as each team could focus on individual subsystems while maintaining communication and a clear understanding of how the components would eventually integrate.

This modular approach not only facilitated simultaneous development but also made AKI adaptable. The modularity allows for the replacement or removal of subsystems if required without significantly impacting the overall system's performance.

As each subsystem was finished, they were integrated into the main program as a subsystem to test if they could work as expected together. The different functionalities were added one by one, and the functionality of the main program was continuously tested during this process to ensure it still ran as expected.

3.2.1 Patterns

The design of emotion-expressive patterns was guided by state-of-the-art research, with six distinct motion modes integrated into the path-planning framework for locomotion control.

3.2.2 Mechanical

To model these subsystems, Computer Aided Design (CAD) software was used. This ensured a precise representation of both new and existing components. The approach involved a combination of modifying old CAD files from the previous design and creating entirely new models where necessary.

The design and functionality of the head, arms, and neck subsystems were largely based on previous iterations of AKI, incorporating work from earlier versions of HK and a master's thesis. The locomotion chassis was designed considering fitting the motors and the shell. Each subsystem was developed independently and underwent individual verification to ensure proper functionality before final integration. Other internal mechanisms were designed carefully to fit each other well.

The components were manufactured in plastic using 3D printers. This method was chosen due to its availability and low cost. 3D printing enabled rapid prototyping for testing and ensured that final manufacturing could be completed quickly.

3.2.3 Electronics

Some of the electronic designs were inherited from previous work, and new designs were achieved for better performance and new features. The processing unit and microcontrollers were chosen considering their performance, price, size, and power consumption.

KiCad was used to build electrical diagrams to plan the electrical connection among different components. The electrical diagrams demonstrate the number of pins needed and how to manage the cables, instruct the choice of the type and quantity of the microcontrollers. The tools from the Mechatronics soldering lab were used to build the electrical connection.

During the design process of the power supply system, the power estimation diagram is used to list the power, voltage, and current needed by all the electrical components. A power distribution diagram is used to demonstrate the power hierarchy. Based on this information, the battery and DC-DC buck converters were chosen, as well as the design for their set-up.

Regarding motor selection for the body movements, the group chose to use the same type (Dynamixels) as in the previous work. For the locomotion, however, the motor selection prioritized the robot's speed requirements, the load capacity of the upper structure, and the voltage and current limitations dictated by the overall circuit design.

3.2.4 Software

Similar to the electrical part, the software consists of both previous work and new design. MATLAB/Simulink was used to build the main program which runs in the main computer UP Core. The program loaded in Arduino boards was developed and tested individually through Arduino IDE. The program loaded in Qt-Py was written in Python. A serial communication protocol was used to build software-level connections between UP Core and microcontrollers.

3.3 Project Organization

This project utilized Trello and Gantt charts as complementary tools to efficiently manage tasks and ensure the project remained on schedule. Trello was primarily used for short-term task planning, while Gantt charts facilitated long-term planning, see Appendix C. Using Trello, each task was broken down into smaller, actionable items, categorized by deadlines, and assigned to team members, allowing for progress tracking at a glance. Importantly, this approach provided greater clarity regarding teammates' activities and progress. To achieve a comprehensive overview of the project timeline, Gantt charts were employed to plan tasks and milestones across the entire project. Tasks were plotted with defined start and end dates, illustrating dependencies between activities. Additionally, regular meetings were conducted to ensure smooth progress. These meetings helped maintain alignment among team members, communicated necessary updates to stakeholders, and facilitated feedback collection to refine the project direction. Key decisions and action items from these meetings were systematically documented in meeting notes, ensuring accountability and traceability.

When allocating subteams, it was considered that the modification of the existing robot and the design of the newly added locomotion could be carried out simultaneously. Therefore, the teams were divided into two parts: locomotion and interior structure. Subteams were formed based on team members' preferences. However, team member switching was implemented in cases where progress on a task stalled or when a member expressed a desire to explore different aspects of the project. This approach aimed to enhance collaboration, promote knowledge sharing, and ensure that each team member gained a comprehensive understanding of the entire project.

4 Implementation

The following section outlines the design and implementation of AKI's subsystems, explaining how each was developed to meet the project requirements. It also discusses the modifications made to each subsystem, the reasons behind these changes, and any additional internal adjustments to the robot's overall design.

4.1 Design and Mechanical Implementation

The mechanical design and implementation consist of the physical, and non-electrical components, with the primary aim of constructing AKI and ensuring its proper functionality. The design of both the external and internal parts of AKI has been modified from the previous version to improve durability and adapt to newly incorporated components, such as those required for locomotion. The final design of AKI, along with an exploded view, is shown in Figure 10.

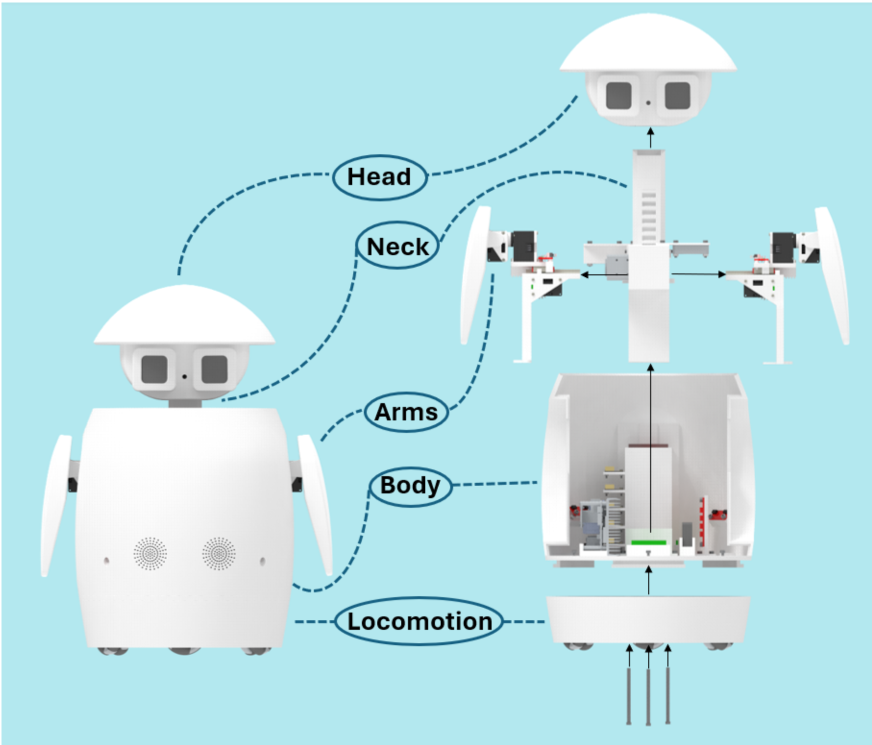
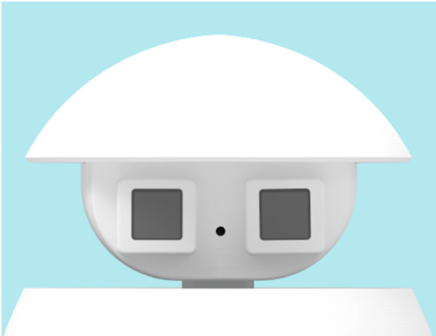


Figure 10: Fully assembled AKI to the left and exploded view to the right with the subsystems marked out

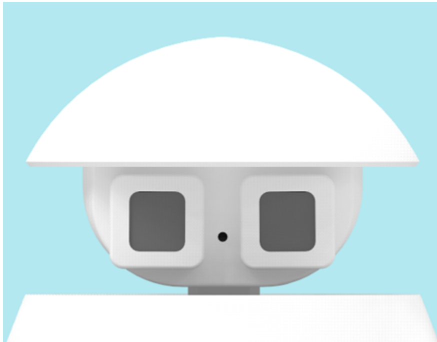
AKI has been divided into five mechanical subsystems: the head, neck, arms, body, and locomotion. Each subsystem consists of parts designed in CAD, which were subsequently 3D-printed using white PLA plastic. The following subsections detail the individual subsystems, highlighting the significant modifications made compared to the previous version.

4.1.1 Head

The design of the head of AKI is mainly unchanged from the previous version. One change that has been made is the eyes. The Liquid Crystal Display (LCD) screens for the eyes have been changed to bigger ones, which has consequently forced changes in the CAD model. The change in size between the old and the new eyes can be seen in Figure 11.



(a) Old eyes



(b) New eyes

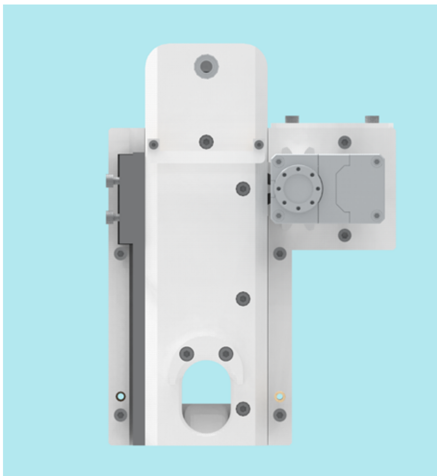
Figure 11: The change in size of the newer eyes compared to the old ones.

The LCD screens are connected to the microcontroller with a ribbon cable. However, this cable is attached quite unconventionally to the LCD screens, which makes it fold a bit. To make it more robust, an attempt was made to change the CAD further so that the cable would not fold as much. The implementation for this was to create an eyebrow-looking cut where the ribbon cable has space to move when the eyes move. Further changes to the CAD models were changing hole parameters to suit threaded insert and 'screw and bolts' better, making mounting and dismounting easier.

4.1.2 Neck

The previous neck design had two main issues: it occupied a significant amount of space as well and it produced some mechanical noise. To address these problems, the neck has been redesigned. In the new design, an electric motor drives a pinion connected to a rack, which moves the neck. Previously, a second rack and pinion were used on the opposite side as a counterbalance. This has been replaced with a linear guide rail. These changes can be seen in Figure 12.

(a) Old neck



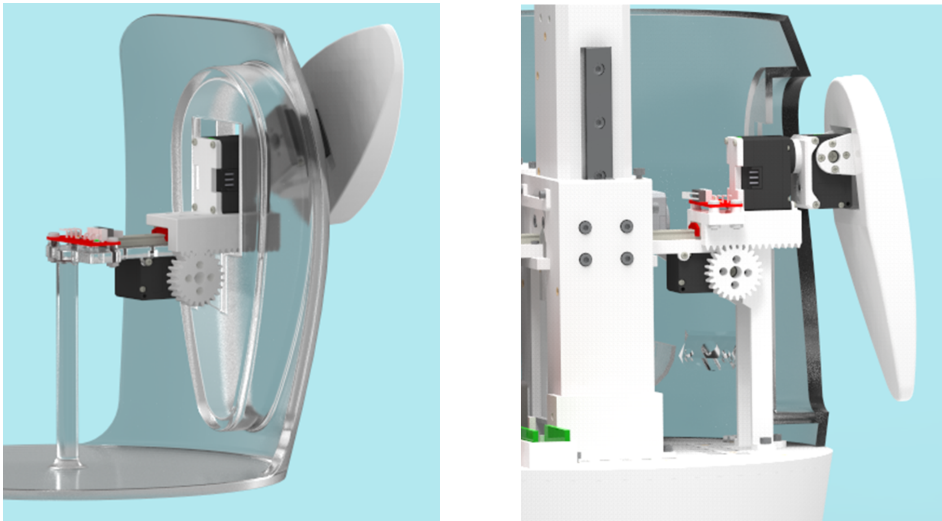
(b) New neck

Figure 12: The change in shape in regard to the neck

The addition of a locomotion module has required routing wires between the locomotion module and the microcontrollers located in the main body. To ensure that the wires are not pinched when the neck is lowered, they are routed through the baseplate and out of the neck, with a dedicated wire path added for protection. Fans have been incorporated for cooling to prevent overheating. The most powerful fan was placed above the UP Core since it was estimated that it would be the hottest component, and the other fan was placed on the opposite side inside the robot. New mounting points have been added to the neck design to support the mounting of these fans.

4.1.3 Arms

The robots' arms were replaced, as a new set with increased functionality had been developed through a master thesis, and the CAD files were provided to the team by the stakeholder. These were implemented in the new robot by making some small changes in the arm design. The master thesis arms had a push sensor in the middle of the robot that can sense when the arms are retracted all the way in. These had to be moved to fit into the robot when the neck was placed in the middle. The old arms and the redesigned version can be seen in Figure 13.



(a) Arm before

(b) Arm after

Figure 13: The current arms compared to the old arms. Viewed from the back of the right arm.

The push sensor was placed on top of the carriage holding the arm. Further, the new version of the arm was made on a freestanding arm holder, and they could hence not be mounted to AKI's shell. In order to make that possible, new mounts were created which had to be designed separately for each side, as the mount merged with the component below it. The left armrest was combined with a holder for the U2D2 in order to save space. The side of the arm holder, not attached to the ground, was mounted onto the neck by a simple shelf construction.

4.1.4 Body

The chosen motors required a minimum bottom diameter to ensure the wheels could rotate freely without hitting or protruding from the shell. This diameter was larger than that of a locomotion module with a height of 5 cm, as specified in the design, while still maintaining the curvature of the shell. To accommodate this, the bottom of the shell was widened, although the top part retained its original shape. This adjustment resulted in a shell that is larger at the bottom, giving AKI a more bullet-like shape rather than an egg-like appearance. Additionally, the inclusion of the locomotion module increased AKI's height by 5 cm. The change in the shape can be seen in Figure 14.

(a) Old shell (b) New shell with locomotion module

Figure 14: The old shell compared to the new shell

To be able to mount the battery properly, a lid was created on the back of the shell, which allows the user to access the interior easily and change the battery. Inside the robot, a battery holder was created so that the battery could be installed properly and connected to the robot's power system. This battery holder also had mountings for the five buck converters, which the system uses to be able to power different components of the robot. To achieve a more robust attachment, threaded inserts have been used instead of the previous design, which involved screwing into the plastic. In areas where threaded inserts could not be placed, nuts and bolts were used instead.

4.1.5 Locomotion

After a comprehensive assessment of factors including accurate maneuverability, directional maneuverability, implementation reliability, space requirements, and visual appearance, combined with feedback from stakeholders, omni-wheels were chosen as the optimal solution.

The locomotion chassis was implemented with three omni-wheels, evenly distributed at 120-degree intervals. To ensure the correct motor selection, a static analysis of the torque and velocity required was performed using rough estimates of the robot's height, weight, and friction coefficient. This analysis did not account for dynamic conditions such as slippage or voltage/current fluctuations etc. The maximum torque from the static analysis was compared with the motor's maximum and efficiency output during operation to verify that the motors could operate within a permissible range for driving the robot. The motor's maximum power output was used to estimate the robot's linear velocity, considering the wheel radius and motor placement. This step ensured that the motors could deliver sufficient power and torque to drive the robot within the allowable velocity range, and overcome the static friction.

The new locomotion features were integrated with the six basic emotions AKI can already express through facial expressions and gestures. Figure 15 illustrates the implemented movements. For happiness, AKI performs a 720-degree rotation. Anger triggers a short, fast-forward movement, while sadness involves a slow, backward J-shaped motion, indicating a desire to be alone. Disgust prompts a slight side rotation. Fear is expressed through a zigzag backward motion to indicate shivering, and surprise results in a sudden backward movement. Other patterns, such as an 8-shape for happiness, were considered. However, the implemented movements were chosen for their simplicity while still maintaining a clear representation of the corresponding emotions.

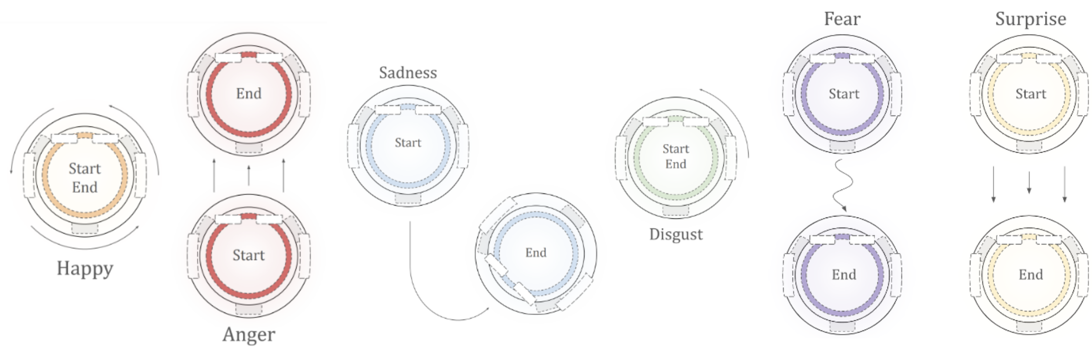


Figure 15: AKI's movements

4.2 Hardware and software

The following section outlines the robot's hardware systems and the corresponding software solutions implemented to control them. It also provides an overview of the main program, detailing how it governs the various emotional responses across the subsystems.

The software development for the robot was organized in a modular fashion, with the system segmented into four primary subsystems: head, arms and neck, locomotion, and sound. This chapter offers a comprehensive examination of the development, implementation, and integration of each subsystem within the broader system architecture.

4.2.1 Main program

To control the subsystems which have been implemented in Simulink, a main program was created. The main program consists of a main loop that chooses which emotion AKI will display. The main loop is made as a state machine using Stateflow in Simulink. A simplified figure of this can be seen in Figure 16.

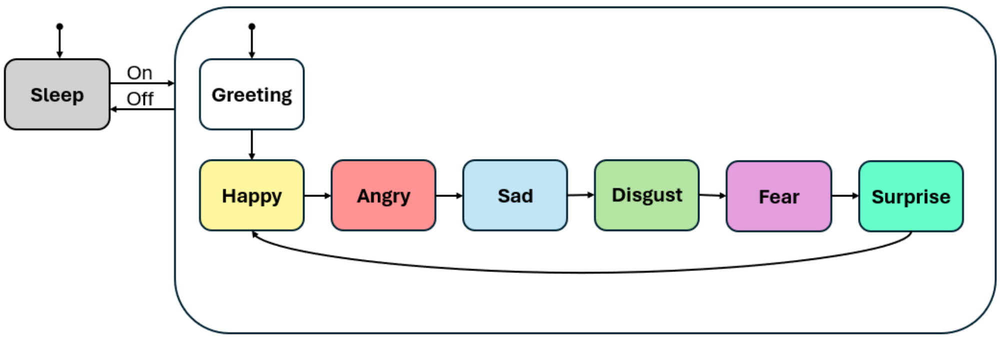


Figure 16: The main loop in the main program

Upon startup, the system enters sleep mode. When activated, it performs a greeting sequence before transitioning into an emotion loop. In the current implementation, there is a time delay between each emotion displayed. The loop continues until deactivation, at which point the system returns to sleep mode.

In each state of the main program, specific commands are issued to the various subsystems. These commands exit the main loop as output and are sent to their respective subsystems as input within Simulink, allowing coordinated control of AKI functions. The architecture of the main program with the main loop and the Simulink subsystems can be seen in Figure 17.

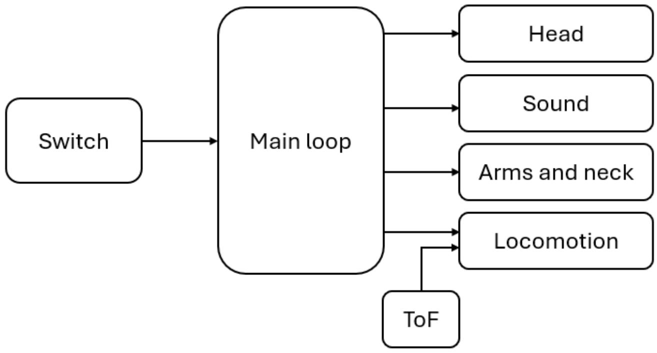


Figure 17: Architecture of the main program

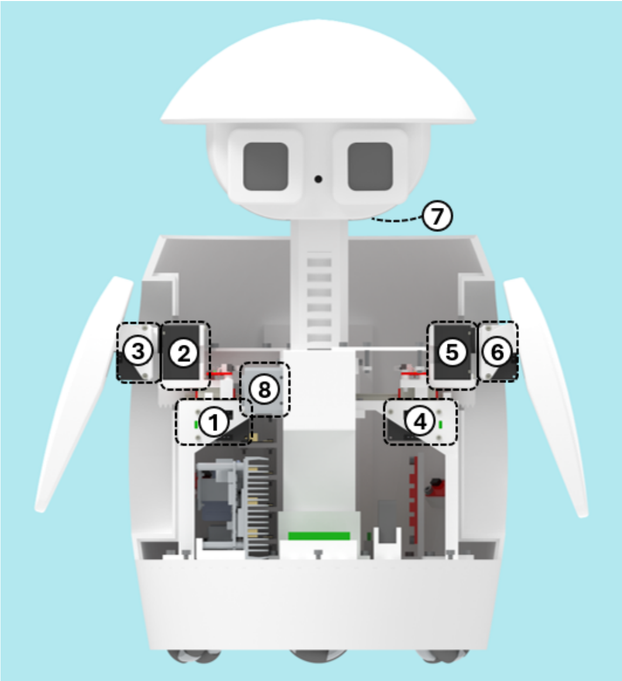
To initiate the system's exit from the sleep state, a switch that can be toggled while the Simulink program is running is used. This switch can either be a pressure sensor physically located inside AKI's head, which is activated by applying pressure to the hat, or it can be triggered remotely within Simulink, allowing for startup from a distance.

4.2.2 Head

The components located in the head are a LED-ring changing color based on the emotion inside the hat. Further, two small servomotors on which the LCD are located, enabling the eyes to rotate. The pressure sensor to wake AKI up is also located inside the head. All these components are connected to a QT-Py. The QT-Py is programmed using Python, with code that manages the selection of eye images, the color of the LED ring, and the reading of the pressure sensor. The program running on the QT-Py communicates with the system by sending a signal when the pressure sensor is activated, and it receives a value that determines which emotion the robot should display through the head components. Input and output data are transmitted via a USB-C cable connected to the UP Core. Input and output data are transmitted via a USB-C cable connected to the UP Core.

4.2.3 Arms and neck

To implement six distinct emotion patterns on the robot's upper structure, a Simulink program that executes the emotions combined with a Matlab script that connects to the Dynamixels and starts the torque is implemented. This setup manages the eight Dynamixel motors connected in sequence, enabling synchronized and continuous movements. This project retains the actuators from the previous design, specifically the XL330 and one XL430 Dynamixel motors from ROBOTIS shown in Figure 18. These motors are chosen for their reliability and compliance, making them well-suited for trajectory planning and expressive robot movements.[6]



ID	Motion	Motor type
1	Arm extension right	Dynamixel XL330
2	Arm rotation right	Dynamixel XL330
3	Arm pitch right	Dynamixel XL330
4	Arm extension left	Dynamixel XL330
5	Arm rotation left	Dynamixel XL330
6	Arm pitch left	Dynamixel XL330
7	Head nod	Dynamixel XL330
8	Neck extension	Dynamixel XL430

Figure 18: The 8 Dynamixel motors, their placement and function

These motors are connected to a U2D2 USB communication converter and a U2D2 power hub. The powerhub is connected to 5 volts and powers the seven XL330 Dynamixels, while the U2D2 itself is powered by the UP Core. The XL430 motor is powered separately with 12 V from the battery. The movements are trajectories of motor positions created by another Matlab script holding the desired motor positions combined with a Simulink program creating trajectory matrices. However, as fewer motors are needed in the new design, the Simulink model and Matlab files had to be modified for the new amount of motors. The execution Simulink file was designed to take in a number from the main program and execute the corresponding emotion. Then, it waits for the locomotion program to finish before moving on to the next emotion.

(a) XL330 (b) XL430

Figure 19: Dynamixel motor models used in AKI

4.2.4 Locomotion

To actuate the locomotion, two different types of motors were considered: Gimbal motors and DC motors. Pros of the Gimbal were its compact dimensions and low noise. However, it had complex connection setups and control, which led to the choice of using the more simple DC motors instead. Considering robot speed requirement, dimension limitation, and load of the upper structure, the chassis is driven by 3 DC motors. These were connected to H-bridge motor controllers, which are controlled using PWM from an Arduino Nano ESP32.

Control theory was mainly applied to the movement of the locomotion wheels. A feed-forward controller was ultimately chosen for the motors. The initial design iteration consisted of a feedback loop with PI velocity control. However, this approach proved unstable in scenarios that involved rapid velocity changes or incorrect encoder readings that caused spikes in the measurements. A low-pass and median filter was implemented to address these encoder spikes. Despite improvements in encoder reading, the control system remained unreliable. Consequently, a simpler and more robust feedforward controller was implemented to ensure stable and accurate motor performance. The controller was designed by first analyzing the system's deadband, the required input power to overcome static friction, and the maximum velocity of the motor. A linear motor model was derived to represent the behavior of the system. The feedforward controller was then developed by inverting the motor model.

To implement the desired driving patterns, MATLAB scripts were developed to generate velocity vectors at specific time intervals. These vectors define the robot's motion by providing the motors with the necessary linear and angular velocities to achieve the intended trajectories.

4.2.5 Time-of-flight sensors

For the obstacle detection, ToF sensors were chosen based on the decision matrix, see Appendix A. The ToF sensors were chosen because they are visually discreet, can measure at a longer distance, give accurate measurements, and are easy to implement. Four ToF sensors were mounted around AKI, with equal distance between them, corresponding to a 90-degree angle. The height and the angle of the sensor were chosen so that it would be able to detect both edges and objects. If one of the sensors receives a distance value lower than what the distance is to the floor, it would interpret it as there being an obstacle and would halt the locomotion movement. If the sensor reads a distance value that is higher than the range of distance that it could be to the floor, it would interpret this as an edge and stop the locomotion movement. The code detecting and interpreting the distances was written in C and ran on an Arduino Nano ESP32. The Arduino communicates this information back to the locomotion part of the main Simulink file. The mount for the sensor was chosen to be in the shell, and the holes were made as small as possible in order for the sensor to look out of the shell without making drastic changes to the robot's appearance. However, these holes created tunnels that do limit the sensor's vision both vertically and diagonally.

4.2.6 Sound

The sound for AKI was created by recording a group member's voice, with one sound designed for each emotion. These recordings were then processed in Logic Pro to sound less human and more robotic. Initially, two hardware options were considered: using an Arduino with an SD card, an amplifier, and two simple speakers or a USB speaker. Since sound implementation occurred late in the project, integrating it with one of the existing Arduinos was avoided to prevent interference with their critical tasks. Instead, the second option was chosen, with sounds stored on the UP Core and played via Simulink sound blocks.

4.2.7 Computing and Processing

To enable AKI's mobility and functionality, a small computer called UP Core 7000 is installed inside AKI. This computer was chosen for its high computation power relative to its small size. It also has a graphics card that can be used in future AI integration works. This computer runs Windows and uses Simulink to execute the programs that control the head, locomotion, neck, and arms. The UP Core functions as the master controller, managing several slave devices, each responsible for specific subsystems: an Arduino ESP32 controls the locomotion, a U2D2 board manages the Dynamixel motors in the arms and neck, and a QT-Py board controls the head. These slaves are connected to the UP Core through USB connections.

The UP Core has a Wi-Fi adapter connected to it that makes it able to connect to the internet.

The Simulink program on the UP Core is accessed remotely via Google Chrome Remote Desktop. A dedicated Google account was created for AKI, and by logging into this account, remote access through the internet to the UP Core is facilitated, enabling control and monitoring of AKI's systems from a distance.

4.2.8 Power Supply System

The robot operates with two different voltage systems. The 5V subsystem includes the Dynamixels for the arm and head, supplied by the U2D2 power hub, and the fans for internal heat dissipation. The 12V subsystem includes the DC motors and drivers for locomotion, two Arduino ESP32 boards for ToF sensors and locomotion control, a QT-Py board for head mechanics control, a U2D2 board for Dynamixels control, as well as the camera and Wi-Fi module.

Appendix E shows the power distribution diagram detailing the power supply relationship for all electronic components in the system. The estimated maximum power consumption for the 5V subsystem is 47W, and for the 12V subsystem is 96W. The power supply system consists of the Turnigy nano-tech 2200mah 3S 45 90C LiPO battery and DFR1015 DC-DC buck converters. The 5V subsystem is powered by two parallel converters capable of supplying up to 50W at 5V; The 12V subsystem is powered by three parallel converters capable of supplying up to 126W at 12V. The converters are powered in parallel, but the output side will be connected to specific components individually in order to avoid unbalanced load among converters.

5 Verification and Validation

Verification of the requirements was conducted using multiple methods, and the results were compared against the permissible levels outlined in the technical specifications. The locomotion module was evaluated for linear and rotational speed as well as noise levels. To test the maximum linear speed, encoder values were recorded while accounting for the 60° angle between the wheel velocity vectors and the robot's direction of motion. Noise levels were measured as the robot executed all its locomotion patterns, and the noise level (dB(A)) was compared with the technical requirements. A battery test was performed by operating the robot under normal conditions and measuring the time elapsed until the battery needed to be changed. Temperature levels were measured using a thermal camera in different scenarios, during start-up idle state and after a certain amount of time while the robot runs at full capacity.

Preliminary tests were also performed on the obstacle detection system. The robot was placed on a table and started to drive its patterns. A successful test was completed if the robot stopped before reaching the table's edge, preventing a fall. Additionally, another test involved a person walking near the robot while it was moving to confirm that the obstacle detection system responded appropriately.

For the requirements that are challenging to verify through direct testing, a detailed rationale is provided in the results section. This includes, among others, the UNICEF guidelines. The validation of the requirements was done in collaboration with the stakeholder to make sure the project satisfied their expectations.

6 Results

To fully evaluate the final design of the robot, a run-through of all requirements given in section 1.4 is needed. Below are the motivations for whether or not the must-have requirements and the nice-to-have requirements were fulfilled.

Must-Have Requirements

1. **Enabling Wheeled Locomotion**
    - **Enabling wheeled locomotion of the robot platform in at least 2 DoF**.
      With the implemented 3-wheeled omni-drive, a movement of 3 DoF was achieved. The robot can move in the plane and rotate around its own axis.
    - **The locomotion shall enhance mobility or the addition of mobility, which creates the potential for higher expressivity.**
      The locomotion allows for a maximum rotation speed of 26 rad/s and a linear velocity of 0.72 m/s.
2. **Ensuring Operational Reliability**
    - **Implementation of rigid components to increase reliability and presentation quality.**
      All components have been reviewed to identify potential improvements. Tolerances have been added and optimized, and sturdier mountings with threaded inserts have been implemented. In many cases, cables have been soldered to ensure more secure connections.
    - **Achieve motion control reliability over extended periods of operation.**
      A preliminary test of the motion has shown to be reliable.
    - **Ensure locomotion noise levels are within permissible ranges for children-robot interaction.**

      The results of the noise test are presented below. The test was conducted by having the robot run through all of its emotions in a continuous loop, which lasted 103 seconds. The minimum noise level detected was 45 dB(A), the average was 55 dB(A), and the maximum was 75 dB(A). In Figure 20, the graph of the noise test is visualized. The noise spikes are from the movement of AKI, and the top spike is from the maximum velocity of the surprised emotion.

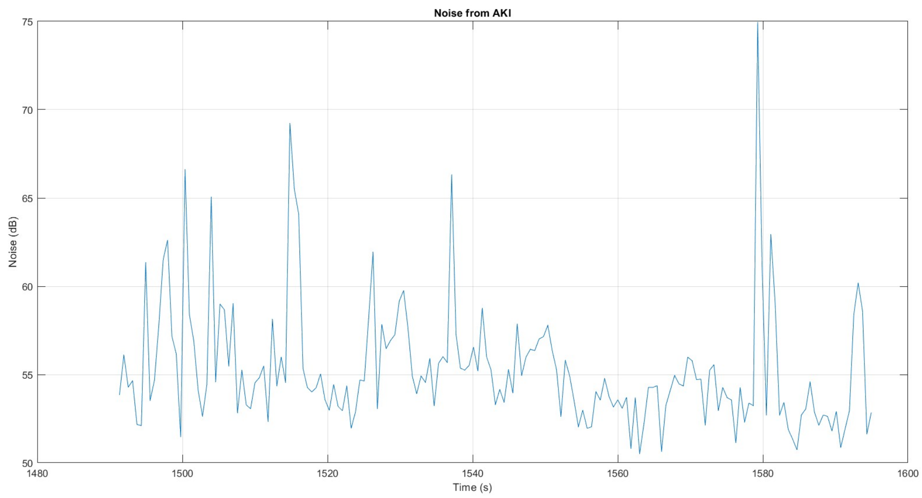


Figure 20: Noise level of all 6 emotions

- **Ensuring the component's temperature level is stable and in an acceptable range under prolonged operation.**

  To ensure stable component temperature levels, a preliminary thermal test was performed. All components started at room temperature (20° C), and the temperature was measured after an initial startup of the system and a 5-minute run of the whole robot. The UP Core was the warmest component, and the temperature of it was 38° C as can be seen in Figure 21.

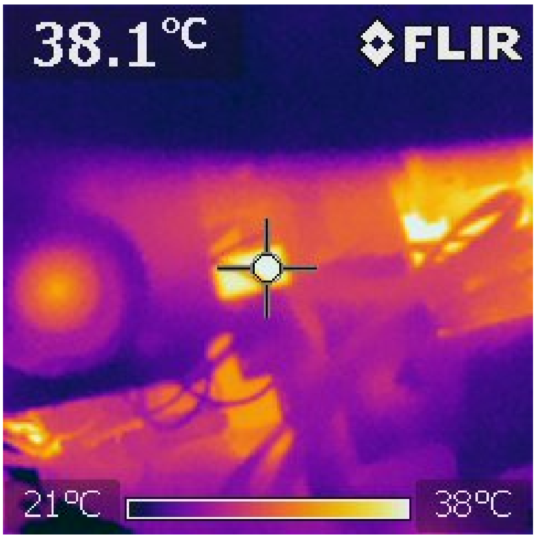


Figure 21: Temperature of UP Core

- **The program code must be modular, facilitating easy testing, and be validated to ensure seamless operation for extended periods without unexpected behaviors.**
  The program is created as a Stateflow in Simulink with corresponding Matlab files.

3. **The robot ensures safe usage for children by complying with UNICEF's requirements 3 & 6.**

   - **Prioritize fairness and non-discrimination for children.**
     Since AKI does not have human attributes such as gender, race, or nationality, it is always capable of communicating from a neutral perspective, which allows AKI to communicate across different ages and cultures.

   - **Provide transparency, explainability, and accountability for children.**
     No major changes were made from the previous robot, and therefore, this should also be valid.

4. **The robot shall be able to operate wireless.**
   The robot operates without wires, using a battery and Wi-Fi connection. It is able to have full functionality for 30 minutes before needing to recharge.

5. **The robot shall detect obstacles and avoid them.**
   The ToF sensors can detect an obstacle from a distance of 9 cm and AKI is able to come to a complete stop before it collides with an object in 5 out of all 6 emotions. During the surprised locomotion pattern, the velocity of AKI is too high for it to stop completely before the collision happens.

Nice-to-Have Requirements:

1. **Enabling Wireless Operation and Communication**

- **Should be able to get data in and out of the robot wirelessly.**
  Data can be transferred to and from the robot using Wi-Fi.

2. **The robot should be able to speak**
   The robot has one sound per emotion.

The dimensions and proportions of AKI have been slightly modified. It is now taller and features a more bullet-like shape compared to the previous egg-shaped design. Additionally, the weight has increased to 4.2 kg, compared to 3.1 kg in the previous model. Further details regarding the technical requirements can be found in Appendix B.

7 Discussion

As was stated in the introduction in Chapter 1, the project's objectives were to develop further an existing robot called AKI, and the most important topics that were chosen to work on can be divided into wheeled locomotion, environment sensing, reliability and the robot being wireless. One topic is also that the robot complies with UNICEF's requirements 3 and 6, but since the previous AKI fulfilled those requirements, this updated version of AKI made sure that those were still fulfilled by the end of this project.

The results indicate a successful implementation, as most of the must-have requirements have been met. However, there was one drawback: the verification of the robot was conducted in the last step of the project, and because there were some unforeseen errors in the robot when it came to validation, there was not enough time left for some of them to be properly carried out. This will be discussed more below.

7.1 Wheeled locomotion

The ability of the robot to move around was one of the main parts of this project. Also, as discussed in Chapter 2.3, the movement of the body is a standout feature that serves as a powerful medium for expressing emotions and intentions. That is why, since the robot can now move in three different degrees of freedom, it now has more potential for higher expressivity than before and has achieved its objective of being able to move around.

After a few ideas of motor control on the locomotion, the chosen method would be to have both a feed-forward and a feedback control, with a PI controller for each motor. That way, they would be able to be controlled properly. Still, because of a shortage of time when implementing the proper controller, only the feed-forward control was chosen, which was satisfactory for those motors to make the robot able to move in its six different locomotion patterns. But when looking back, this should have had a higher priority earlier on in the project so the group would not have had this shortage of time by the end of the project.

Wheeled locomotion also allows possibilities for new implementation of what AKI could do. For example, it leaves the option open for AKI to be able to map an area by sensing its surroundings and be able to navigate through with path planning. AKI could also charge itself by navigating to its own charging station if that were implemented. The wheeled locomotion also allows for better interaction with children if AKI will be able to tell stories or play games.

Additionally, with locomotion, AKI becomes more similar to other robots that are being used today, like, for instance, Buddy, who also has wheels and sensors to detect the surrounding area. 2.1.2.

7.2 Environment sensing

The results in Chapter 6 indicate that the desired obstacle avoidance was not achieved. The reason is that AKI could not come to a complete stop before it collided with an object when it drove in the locomotion pattern of being surprised, even though it was able to stop when expressing all other emotions. This, however, is a pretty big flaw as the robot is supposed to be used by kids, so ensuring they are safe by not colliding with them is a top priority for this project. This could also be damaging to AKI itself as he is supposed to detect table edges to stop himself from falling off a table, which could result in him breaking and losing the ability to function properly.

However, the reason this part of the project did not work as desired was that the validation of the sensors worked properly and was conducted so late in the work process, as the whole robot had to be finished and assembled before the sensors could be tested properly on AKI. Therefore, there wasn't any time to redesign parts that would solve this issue. For instance, the sensors' inability to detect obstacles further away is due to their placement, view, and angle of the robot. They were chosen to be as low as possible in AKI's shell, angled 45° downward, and sensed through as small a hole as possible to make it as little noticeable as possible.

To fix this issue, however, one of these three things, the height of the sensor, the angle of the sensor, or the see-through hole, could be changed in the shell to make the sensor able to sense further away.

7.3 Reliability

The results show that a big part of this project was reliability. For instance, all rigid parts of the old 3D models of AKI had to be remade to improve the structure and tolerances of AKI. For instance, the old model lacked mounts where the microcontrollers and PCBs of the robot could be mounted, so in the new model, they were mounted where they would not put any stress on any of the wires, given all possible movement that the robot could move in.

Also, some of the old 3D models of AKI interfered with each other, and in the old Fuyu robot, that was fixed by scraping some of the material off. That meant that some parts had to be redesigned in CAD, which overall improved the structural strength of AKI.

The validation of the thermal properties could be further validated by further measuring of temperature.

7.4 Wireless

The results in Chapter 6 show that the robot's full functionality with wireless capabilities was successfully achieved. This allows a lot of new possibilities for AKI, who, previously, was not able to move around at all because of the cables that controlled his movements and powered him up. However, since AKI is powered by a battery and is controlled through a Wi-Fi connection, AKI is now able to move around freely, as was done in this project.

However, as well as being able to move around freely, being wireless also allows AKI to be used in a lot more diverse surroundings, as it is no longer reliant on being near an outlet and a computer that controls it. This also makes AKI more similar to existing social robots like EMO and Buddy, who are both wireless, which is a quality that is important for social robots to have 2.1. There is one limitation of being wireless, and that is that the robot needs to have its battery changed after 30 minutes of full functionality.

8 Future Work

This chapter introduces a few suggestions on what the future work might be. The first thing that can be implemented is, for example, the nice-to-have requirements that the group did not have time to implement, which can be seen below.

- The robot should be able to take user interactions (e.g., verbal instructions, visual directions) and transfer them into movements.
- Enabling usage of AI tools for user communication and creating a visual, emotional reaction from the robot based on the user's input.
- The robot should be able to move away from obstacles.
- Sensor data for extracting knowledge and information about the physical environment (users, obstacles).

In addition to implementing the nice-to-have, other future work is discussed below.

8.1 Sensing

Improvements could be made to ToF sensors to improve the detection of obstacles and edges of AKI. The selected ToF sensors are able to measure distances in a 3×3 grid, but in the current iteration of the project, only the central point is being measured. AKI could have a wider field of view if the whole 3×3 grid is measured. This is currently restricted by the size of the hole, which could be made bigger at the cost of making the holes less discreet. Also, as mentioned in 7.2, changing the angle of the ToF sensor could allow the sensor to detect an obstacle or an edge further away, but at the cost of being less discrete. Furthermore, putting the sensors higher up in the shell of AKI will also increase the range that AKI can detect obstacles and edges, but that also might make AKI less appealing as then it would have to have its sensor holes higher up in the shell.

8.2 Movement

The control algorithm could use feedback for a more consistent movement. The current implementation moves well in the sense that it manages to convey the emotion, but its final placement after the pattern has been moved varies. This could be improved by filtering the encoder readings to give a more consistent reading, then using the error between the reference value and the encoder readings with a PD control and sum it with the feed-forward control.

There is room for improvement in emotional expression. Sometimes, AKI does not execute all the subsystems at the same time, such as the arms, locomotion, and sounds. One way this could be improved is to lessen the computational load on the Up Core.

8.3 Wireless

There are also a few improvements that can be worked on regarding powering up AKI. Currently, the battery that is being used supplies AKI with enough power for it to function for 30 minutes with full functionality before needing to recharge. One thing that could be changed is having a longer-lasting battery so the robot would last longer before needing to have its batteries changed. Also, the hatch on the back side of AKI, which seals the battery inside AKI, can be changed to make it more user-friendly. Currently, it has to be fastened using a screw, but there can be a way for it to be fastened mechanically without the use of screws, which would make it more user-friendly.

The best way to continue working on powering up AKI, though, would be if there would not even be a need to change AKI's batteries anymore, and instead, he could be charged up. That way, there would not even be a need for a hatch for the battery so that the shell would look smoother. Also, since the robot now has locomotion and the possibility of mapping and navigating through its surroundings, there is a possibility of making AKI able to charge itself by driving to a charging port where it could be charged.

8.4 Enhanced User Interaction

As well as the work mentioned above, to further develop the robot, the robot needs to have enhanced user interaction for it to be able to reach its desired functionality of interacting with children.

Future work would be to implement a camera and a microphone for the robot so that it can interact better with the user. Also, it would need added functions in its software to make the robot able to react to the user with proper emotion.

Another thing that can be implemented is improved speech of AKI, which allows AKI to communicate verbally with the user. Since social robots like AKI can serve as assistants in classrooms and hospitals, as mentioned in Chapter 1.1, they need to be able to communicate verbally with the user.

References

[1] R. Vestman, "A comparative study of omnidirectional and differential drive systems for mobile manipulator robots: A performance review of strengths and weaknesses," Dissertation, 2023. [Online]. Available: https://urn.kb.se/resolve?urn=urn:nbn:se:kth:diva-332431

[2] Swerve drive. [Online]. Available: https://compendium.readthedocs.io/en/latest/tasks/drivetrains/swerve.html#:~:text=Swerve%20Drive%20is%20a%20type,above%20in%20the%20rightmost%20image.

[3] B. Shamah, "Experimental comparison of skid steering vs. explicit steering for a wheeled mobile robot," p. 54, 1999.

[4] Ir sensor : Circuit diagram, types working with applicationsg. Accessed: 17.05.2024. [Online]. Available: https://www.mathaelectronics.com/ir-sensor-circuit-diagram-types-working-with-applications/

[5] Photoelectric basics – distance measuring. Accessed: 17.05.2024. [Online]. Available: https://automation-insights.blog/2016/03/30/photoelectric-basics-distance-measuring/

[6] L. Algot, P. Annie, A. Christos, P. Frhim, F. Joel, B. Johanna, B. Marcel, and S. Maria, "Development of an emotionally expressive robot platform," *MF2059 KTH Mechatronics Advanced Course*, 2022. [Online]. Available: https://www.diva-portal.org/smash/get/diva2:1738912/FULLTEXT01.pdf

[7] H. Woo, G. K. LeTendre, T. Pham-Shouse, and Y. Xiong, "The use of social robots in classrooms: A review of field-based studies," *Educational Research Review*, vol. 33, p. 100388, Jun. 2021.

[8] A. Raptopoulou, A. Komnidis, P. D. Bamidis, and A. Astaras, "Human–robot interaction for social skill development in children with asd: A literature review," *Healthcare Technology Letters*, vol. 8, no. 4, pp. 90–96, 2021.

[9] K. Dautenhahn, "Socially intelligent robots: dimensions of human–robot interaction," *Philosophical Transactions of the Royal Society B: Biological Sciences*, vol. 362, no. 1480, pp. 679–704, Feb. 2007.

[10] L. AI. (2024) Emo - living ai. Accessed: 29.04.2024. [Online]. Available: https://living.ai/emo/

[11] Blue Frog Robotics. (2024) Buddy user guide. Accessed: 26.04.2024. [Online]. Available: https://www.bluefrogrobotics.com/wp-content/resources/guides/Userguide-Buddy_EN.pdf

[12] A. G. H. Huettenrauch, K. S. Eklundh and E. A. Topp, "Investigating spatial relationships in human-robot interaction," *2006 IEEE/RSJ International Conference on Intelligent Robots and Systems*, pp. 5052–5059, 2006.

[13] T. Ono, M. Imai, and R. Nakatsu, "Reading a robot's mind: a model of utterance understanding based on the theory of mind mechanism," *Advanced Robotics*, p. 311–326, 2000.

[14] M. A. N. E. Saad and K. V. Hindriks, "Welcoming robot behaviors for drawing attention," *2019 14th ACM/IEEE International Conference on Human-Robot Interaction (HRI)*, pp. 368–368, 2019.

[15] R. Gockley, A. Bruce, J. Forlizzi, M. Michalowski, A. Mundell, S. Rosenthal, B. Sellner, R. Simmons, K. Snipes, A. Schultz, and J. Wang, "Designing robots for long-term social interaction," *IEEE 2005 IEEE/RSJ International Conference on Intelligent Robots and Systems*, 2005.

[16] T. Kanda, T. Hirano, D. Eaton, and H. Ishiguro, "Interactive robots as social partners and peer tutors for children: A field trial," *Human–Computer Interaction*, pp. 61–84, 2004.

[17] T. Kishi, T. Endo, N.; Nozawa, T. Otani, S. Cosentino, M. Zecca, K. Hashimoto, and Takanishi, "Bipedal humanoid robot that makes humans laugh with use of the method of comedy and affects their psychological state actively," *IEEE 2014 IEEE International Conference on Robotics and Automation (ICRA)*, 2014.

[18] A. LEJDEBY and K. HERNEBRANT, "Omni wheel robot," Dissertation, 2016, available online: https://urn.kb.se/resolve?urn=urn:nbn:se:kth:diva-191520.

[19] M. J. Bjärenstam and M. Lennartsson, "Development of a ball balancing robot with omni wheels," Examensarbete för Yrkesexamen (Avancerad nivå), Institutionen för reglerteknik, KTH Royal Institute of Technology, Stockholm, Sweden, 2012. [Online]. Available: URL_of_the_document

[20] P. Gautam, S. Sahai, S. Kelkar, M. Reddy D, and P. Agrawal, "Designing variable ackerman steering geometry for formula student race car," *International Journal of Analytical Experimental and Finite Element Analysis (IJAEFEA)*, vol. 8, pp. 1–11, 02 2021.

[21] J. Batlle and A. Barjau, "Holonomy in mobile robots," *Robotics and Autonomous Systems*, vol. 57, pp. 433–440, 04 2009.

[22] R. P. M. Chan, K. A. Stol, and C. R. Halkyard, "Review of modelling and control of two-wheeled robots," *Annual Reviews in Control*, vol. 37, no. 1, pp. 89–103, 2013. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S1367578813000060

[23] T. SATO and T. MORI, "Expression of emotion and intention by robot body movement," p. 8.

[24] M. Zecca, Y. Mizoguchi, K. Endo, F. Iida, Y. Kawabata, N. Endo, K. Itoh, and A. Takanishi, "Whole body emotion expressions for kobian humanoid robot — preliminary experiments with different emotional patterns —," in *RO-MAN 2009 - The 18th IEEE International Symposium on Robot and Human Interactive Communication*, 2009, pp. 381–386.

[25] A. Melzer, T. Shafir, and R. P. Tsachor, "How do we recognize emotion from movement? specific motor components contribute to the recognition of each emotion," *Frontiers in Psychology*, vol. 10, 2019. [Online]. Available: https://www.frontiersin.org/journals/psychology/articles/10.3389/fpsyg.2019.01389

[26] H. Parvez. 14 sad body language signs. [Online]. Available: https://www.psychmechanics.com/sad-body-language-signs/

[27] ——. Facial expressions: Disgust and contempt. [Online]. Available: https://www.psychmechanics.com/facial-expressions-disgust/

[28] What is surprise? [Online]. Available: https://www.paulekman.com/universal-emotions/what-is-surprise/

[29] What is an ir sensor : Circuit diagram & its working. Accessed: 17.05.2024. [Online]. Available: https://www.elprocus.com/infrared-ir-sensor-circuit-and-working/

[30] Croma. Buy cliff sensors online at best prices. Accessed: 17.05.2024. [Online]. Available: https://www.croma.com/l/cliff-sensor-0afz07a.html#:~:text=A%20cliff%20sensor%20is%20a,or%20avoid%20the%20obstacle%20altogether.

[31] G. B. U. Inc. The sensor technologies behind autonomous navigation. Accessed: 17.05.2024. [Online]. Available: https://www.gideon.ai/resources/3d-depth-sensing-for-robots-101/

[32] The sensor technologies behind autonomous navigation. Accessed: 17.05.2024. [Online]. Available: https://www.gideon.ai/resources/3d-depth-sensing-for-robots-101/

[33] Kentfaith. What is a monocular camera ? Accessed: 17.05.2024. [Online]. Available: https://www.kentfaith.co.uk/blog/article_what-is-a-monocular-camera_72#:

~:text=a%20Monocular%20Camera-,A%20monocular%20camera%20is%20a%20type%20of%20camera%20that%20uses,surveillance%20systems%2C%20and%20autonomous%20vehicles.

[34] Advantages and disadvantages of time-of-flight cameras. Accessed: 17.05.2024. [Online]. Available: https://www.framos.com/en/articles/advantages-and-disadvantages-of-time-of-flight-cameras

[35] Mechanical wear. [Online]. Available: https://d1wqtxts1xzle7.cloudfront.net/33794949/Wear_Erosion_Testing-libre.pdf?1401118275=&response-content-disposition=inline%3B+filename%3DWear_Erosion_Testing.pdf&Expires=1713801996&Signature=Wu5ORntCr1mmY6mxxbtNatoLDftALa8wjSLMu-PpW1RqoFDVy0p3YmLLzKAI-N023OnRcqE4wEys~q-_&Key-Pair-Id=APKAJLOHF5GGSLRBV4ZA

[36] Friction and mechanical wear. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S1000936117302637?via%3Dihub#b0015

[37] V. Arun, R. Kannan, S. Ramesh, M. Vijayakumar, P. S. Raghavendran, M. S. Ramkumar, P. Anbarasu, and V. P. Sundramurthy, "Review on li-ion battery vs nickel metal hydride battery in ev," *Advances in Materials Science and Engineering*, 2022.

[38] L. Y, Z. C-Z, and e. a. Yuan H, "A review of rechargeable batteries for portable electronic devices," 2019.

[39] M. Zhu and O. Schmidt, "Batteries for small-scale robotics," *MRS Bulletin 49*, p. 115–124, 2024.

[40] Short-range wireless technologies. [Online]. Available: https://utsa.pressbooks.pub/networking/chapter/short-range-wireless/

[41] Y. Yu, L. Zheng, and e. a. Jianjie Zhu, "Technology of short-distance wireless communication and its application based on equipment support," 2018.

[42] S. Farahani, "Zigbee wireless networks and transceivers," 2008.

A Decision Matrices

Criteria	Factor (1-5)	Omni Wheels	Mecanum Wheels	Differential Drive	Swerve Drive	Ackerman/ Tricycle	Synchro Drive	Skid Steering	Legs
Accurate maneuverability	2	3	2	3	4	5	5	5	1
Directional maneuverability	5	5	5	2	5	1	4	2	1
Easy implementation	2	4	2	5	1	5	1	4	1
Reliability	5	3	3	5	1	5	1	4	1
Required space	4	3	1	5	1	2	1	2	1
Visual appearance	2	4	1	3	5	1	5	3	5
Sum		74	54	77	54	60	51	62	28

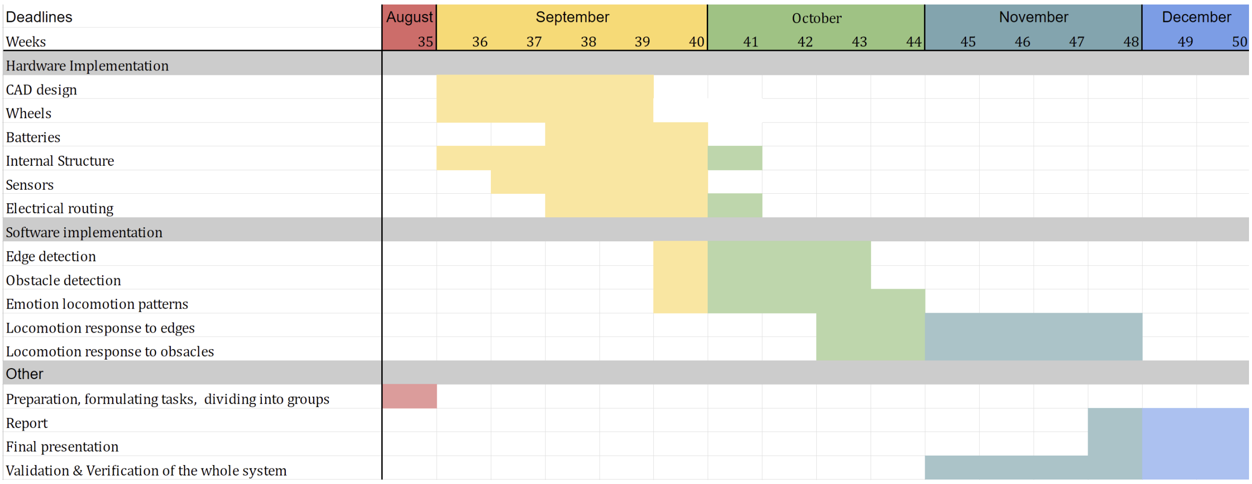
		Edge Detection	Obstacle Detection	Both			
Criteria	**Factor (1-5)**	**Cliff Sensor**	**Lidar**	**Monocular Camera**	**IR Sensor**	**ToF**	**Stereo Camera**
Distance	4	1	5	2	3	5	5
Weight	1	5	1	4	2	4	2
Size	2	5	1	4	5	4	2
Accuracy	5	4	3	1	4	5	4
Easy Implementation	3	5	3	2	2	4	2
Visual Appearance	5	5	1	4	3	4	2
Computer Processing	1	5	5	1	5	4	2
Sum		89	58	56	77	97	66

B Technical Requirements

Tabell 2. Requirements specification developed for AKI.

Demands (D) / Wishes (W)	Type	Description	Accomplished
Locomotion			
At least 2 DOF	D	The locomotion shall allow forward and backwards, aswell as rotation along z-axis	Yes
Maximum wheelsize 7 cm in diameter	D	To keep current apperance	Yes
Top speed of minimum of 40 cm/s	D		Yes
Rotational speed of minimum 120 degrees/s	D		Yes
The robot shall be capable of stopping from full speed before colliding	D		No
The robot should move to a specific area	W		No
The robot shall have one type of locomotion pattern per emotion	D		Yes
Reliability			
The thermal equilibrium of the components in the robot shall not exceed 80 % of their maximum temperature	D		Yes
The outside of the robot shall not exceed 10 degrees above room mean temperature	W		Yes
The robot shall have error reporting features	D		Partly
A manual and a wireless off switch (E-Stop)	D	For safety reason	Partly
The robot should be able to be disassembled in less than 60 minutes	W		Yes
The noice level shall not exceed 80 dB(A) one meter from the robot	D		Yes
Wirelessness			
The robot shall have a minimum operating time of 1/2 hour during average operation in a single charge	D		Yes
Charging 0 - 80 % will take less than 40 minutes	W		Yes
Obstacle detection			
The robot shall be able to detect an obstacle less than 20 cm in front of it	D		No
The robot shall be able to detect an edge less than 20 cm in front of and behind it	D		No
The robot should swivel around an obstacle	W		No
The robot shall avoid collision and falling off an edge	D		Yes
The robot should drive away from an edge	D		No
Communication			
The robot should be able to respond to movement by user, by moving or speaking	W		No
The robot should be able to react to voices by moving	W		No
The robot should be able to react to voices by speaking back	W		No
The robot should use child friendly language	W		Yes
The robot should not store any personal data after it has been turned off	D		Yes
Dimensions			
The addeed weight shall not exceed more than 50% of current weight	W		Yes
The design of proportions of AKI shall not be changed	D		No
The center of mass shall be as close to the bottom as possible	D		Yes
The dimensions of the robot shall not be changed without consultation from stakeholder	D		Yes

C Project Plan



D Failure Mode Effects Analysis (FMEA)

Failure Mode	Effect	Severity (1-10)	Cause	Occurrence (1-10)	RPN	Recommended Action
Wheel mechanism failure	Robot becomes immobile	5	Weak motors, Bad implementation,	6	30	Use higher quality components. Review the implementation
Battery failure	Unexpected shutdown	2	Weak battery, loose cables, battery degradation	7	14	Implement battery redundancy
Wireless communication loss	Loss of control	1	Signal interference	10	10	Use more reliable modules
Obstacle sensor failure	Obstacle sensor failure	10	Sensor malfunction	2	20	Add backup sensors, improve algorithms
Mechanical wear and tear	Performance degradation	7	Lack of lubrication, loose cables material fatigue	6	42	Add more lubrication, Reduce friction
Sensor Malfunction	Inaccurate data	10	Calibration errors, current sensor (cut off fingers) physical damage	1	10	Improve sensor calibration, implement redundant sensors
Environmental Hazards	Component damage	7	exposure to warm temperatures, moisture	1	7	Implement environmental sealing, relocate sensitive components
Software Bugs or Glitches	Unexpected behaviour	7	Programming errors, inadequate testing	8	56	Improve software testing procedures
Integration Hell	Unexpected behaviour	7	System is not collaborating	10	70	Time consuming troubleshooting
Group problem	Disagreements, miscommunication scheduling	4	Complex development process	3	12	Code of conduct, regular meetings
Failure to procure components	The project gets delayed	5	Delay in manufacturing and shipping	3	15	Find other similar components, wait and work on other things

E Power Distribution