THE POWER OF PLAY;

DEVELOPING AND EVALUATING A SENSOR ENHANCED PLUSHIE AS AN INTERACTION TOOL TO ROBOT MIRO TO IMPROVE AND ASSESS THE WELLBEING OF POST-OPERATIVE CHILDREN

D. (Danique) Damen

MSC ASSIGNMENT

Committee:
dr. F.J. Siepel
dr. ir. E. Dertien
dr. ir. M. Vlutters

March, 2024

010RaM2024
Robotics and Mechatronics
EEMCS
University of Twente
P.O. Box 217
7500 AE Enschede
The Netherlands

Abstract (EN)

This research is part of a larger project named “Hospital Environment Linked Pain Evaluation Robot” (HELPER) which aims to use robotics to evaluate and improve the wellbeing of children post-operatively. In previous research for this project, the potential is seen for the clinical usage of a robot for pain management and stress relief. Hospital settings could induce stress and a communication barrier between the child and staff. Consequently, the child could experience anxiety, loneliness and undertreated pain, which could lead to an instantaneous or ongoing increase of pain, an extended recovery period, anxiety and effects in the long term. With current wellbeing assessment tools, the hospital staff needs to observe the child for behavioural symptoms of pain since children of the target group (aged 3-5) cannot express themselves accurately verbally.

Development plushie

Therefore, continuous monitoring of wellbeing could contribute to improving this method. However, the robot can not be in the hospital bed with the child because of hygiene reasons and its mechanical, heavy structure. Nonetheless, physical contact could alleviate pain, which is why this thesis aims to develop a plushie with integrated sensors to indicate the wellbeing of the child while being a valuable supplement to the robot with respect to bringing distraction and companionship. It is chosen to enhance the plushie, prototyped as a magic wand, with a microcontroller with an embedded Inertial Measurement Unit (IMU) and microphone, capacity pads and a pressure sensor. With that, interactions, such as shaking, squeezing and talking, can be measured. The child’s interactions can be translated to a child’s behaviour.

Testing

The core of this thesis is a paper in which the developed prototype is tested with healthy children to explore its potential. Therefore, three phases, including self-exploration, games and a story, are designed to test the plushie and robot combination. The sensor data is saved during these tests, and a pedagogical scientist documents observations of the child’s behaviour. Consequently, the mean values for each sensor for each child are calculated. For easier comparison, the deviation from the mean of all children is derived.

Results

It is seen that children understand the interactions possible and the robot’s reactions. They seem to enjoy physically interacting with the plushie and the possibilities of the technology. Therefore, a plushie is of added value to the robot. Furthermore, the profile sketch of each child matches the mean of the sensor data of the interactions with the plushie, which means it can be linked to the child’s behaviour. Since a child’s behaviour indicates their wellbeing, including a plushie shows excellent potential for future wellbeing enhancement and assessment.

Abstract (NL)

Dit onderzoek is onderdeel van een groter project genaamd "Hospital Environment Linked Pain Evaluation Robot", met als doel het welbevinden van een kind te evaluaren en verbeteren na een operatie. Uit eerder onderzoek voor dit project bleek al dat de gekozen robot potentie heeft tot het managen van pijn en het verminderen van stress. De ziekenhuisomgeving kan erg stressvol zijn voor een kind en er kan een communicatiebarrière ontstaan tussen het kind en het personeel. Hierdoor kan het kind angst, eenzaamheid en/of onderbehandelde pijn ervaren, wat weer kan leiden tot directe of langdurige verergering van pijn, een langere herstelperiode, angst en andere lange termijn effecten.

Huidige methoden om welbevinden te bepalen bij een kind vereisen observaties van een medewerker om symtpomen in het gedrag van het kind te ontdekken die te maken kunnen hebben met pijn gezien kinderen in de target groep (3-5 jaar oud) zichzelf nog niet genoeg verbaal kunnen uiten.

Ontwikkeling knuffeltje

Daarom kan continue meten van pijn een toevoeging zijn om deze methode te verbeteren. Alleen kan de robot om hygiene en mechanische redenen niet bij het kind in het ziekenhuisbed terwijl pijn kan worden verlicht door het hebben van fysieke interactie. Daarom is het doel van deze thesis om een knuffeltje te ontwikkelen met geintegreerde sensoren die een indicatie kunnen geven over het welbevinden van het kind terwijl deze plezier haalt uit de interacties. Een prototype van het knuffeltje is gemaakt in de vorm van een toverstaf met een microcontroller met een Inertial Measurement Unit (IMU) en een microfoon, capaciteit pads en een druk sensor. Daarmee kunnen interacties als schudden, knijpen en praten worden vastgelegd. Het gedrag van het kind kan worden gehaald uit de interacties die het kind heeft met de knuffel.

Testen

Het middelpunt van deze thesis is een paper waarin de potentie van het ontwikkelde knuffeltje is getest met gezonde kinderen. Daarom zijn er drie fases ontwikkeld, zelf verkennen, spelletjes en een verhaaltje, om het knuffeltje in combinatie met de robot te testen. Tijdens de tests zijn de kinderen geobserveerd door een pedagoog en is de data van de sensoren opgeslagen. Vervolgens is het gemiddelde bepaald voor iedere sensor voor ieder kind. Voor het vergelijken van de data is de afwijking van het gemiddelde voor ieder kind bepaald.

Resultaten

De kinderen begrijpen de interacties en responderende reacties van de robot. Ze zijn geinteresseerd en lijken plezier te hebben in het aanraken en spelen met de knuffel en de mogelijkheden van de robot en het het vermaak. Daarom is de knuffel een goede toevoeging aan de robot voor het verbeteren van het welbevinden van een kind. Daarnaast komen de profielschetsen overeen met de gemiddelde afwijking van het gemiddelde van de interacties die ze hebben met de knuffel. De sensordata kan dus aan het gedrag van het kind worden gelinkt. De plushie heeft dus ook potentie voor het bepalen van het welbevinden van een kind, gezien het gedrag hiervoor indicatief is.

Preface

As I became more passionate about robotics, I started my master's in biorobotics. When I started my master's thesis in March, I found myself getting hard to motivate. When I decided to switch assignments and started working on this topic, I got enthusiastic about all the possibilities of robotics beyond exoskeletons. Guided by my daily supervisor dr. ir. Edwin Dertien, I got captivated by the creative implementation possibilities of robotics in various contexts and discovered social and interactive robotics. Thank you, Edwin, for showing me these possibilities.

Driven by my curiosity and desire to learn new skills, I found a perfect match in my assignment. I got to tinker with hardware and software and implement it for a healthcare purpose aligned with my identity as a biomedical engineer, a perfect opportunity to prove my competencies in this master's thesis.

Therefore, I am especially happy to be able to include dr. Ir. Mark Vlutters as an external member of my graduation committee as I can show him my academic development since 2.5 years ago when I presented my bachelor thesis under his supervision. Additionally, I want to thank dr. Françoise Siepel for the positive feedback and for taking the time to supervise me.

Not to forget my fellow researcher, Ilse Voogd, who observed the children during the tests. Thank you for your positive attitude, for de-stressing me with fun, for taking your time to help, and for your clear notes. Furthermore, I appreciate Jasper Hoekstra's time and detailed feedback on my writing. Also, I should not forget to thank "The breakfastclub", Luka, Ilse and Boudewijn, for putting me to study every morning. Additionally thanks to everyone who helped me throughout the process by just listening to me or helping me in any other way.

Structure

The structure of this thesis diverges from the conventional structure as it is centered around a paper (part II). The paper details the tests conducted with my developed prototype. Yet, one can imagine that the development process is time-consuming. Therefore, the elaboration of the steps taken leading to the prototype is provided in the appendix. For a more detailed background understanding, the context of the topic is explained (part I).

Have fun reading!

Table of Contents

Definitions

Preschoolers/ Target group	Children aged 3-5 years.
Wellbeing	The state of feeling happy and healthy.
MiRo	The commercially available robot used for the HELPER project.
Plushie	A plushie with integrated sensors is developed and evaluated for this thesis.
Phase 1	The self-exploration phase of the tests. MiRo responds to the interactions with the plushie.
Phase 2	The games dance party, guess the animal and Simon says.
Phase 3	The interactive story with the plushie and the magic wand.
Master-slave	A type of device connection in which one device controls (master) one or more other device(s) (slave(s)).
Server-client	A type of device connection in which the server advertises services and the client requests these services. One server can provide multiple clients with its services.
Peripheral-central	A type of device connection in which the peripheral connects to the central, which manages its functions. A peripheral can only connect to one central.

Abbreviations

ADC	Analog to Digital Converter
AI	Artificial intelligence
ANN	Artificial neural network
ANS	autonomous nervous system
Async(io)	Asynchronous Input/Output
BLE	Bluetooth Low Energy
Bleak	Bluetooth Low Energy platform Agnostic Klient
BP	Blood pressure
CAP	Capacity sensor
CHEOPS	Children's Hospital of Eastern Ontario Pain Scale
cos	cosmetic
CPU	Central Processing Unit
CS	Chip Select
DoF	Degrees of freedom
ECG	Electrocardiogram
EDA/GSR	Electrodermal activity/Galvanic skin response
EMG	Electromyography
FFT	Fast Fourier Transform
FLACC	Face, Legs, Activity, Cry and Consolability
GAP	Generic Access Profile
GATT	Generic Attribute Profile
GIL	Global Interpreter Lock
HELPER	Hospital Environment Linked Evaluation Robot
HRI	Human-robot interaction
I2C	Inter-Integrated circuit
IBD	Interaction based design
IDE	Integrated development environment
IMU	Inertial measurement unit
IO	Input/Output
kin	kinematic
MDK	MiRo development kit
MC	Microcontroller
MOSI/MISO	Master Out Slave in
ML	Machine learning
PC	Portable computer
PCM	Pulse Code Modulation
PPG	Photoplethysmography
RF	Radio frequency
ROS	Robotic operating system
RX	Receiver part of UART
SBD	Scenario Based Design
SC	Skin conductance
SCK/SCL	Serial Clock
SPI	Serial Peripheral Interface
SSH	Secure Shell
TRL	Technology readiness level
TX	Transmitter part of UART
UART	Universal Asynchronous Receiver/Transmitter
UCD	User-centred design
URL	uniform resource locator
uuid	Universally unique identifier
Wi-Fi	Wireless Fidelity

Part I
Research context

As this thesis revolves around a paper (part II), it is not written in the usual form. In the paper, the research that explores the power of play with robotics as a tool for wellbeing assessment and improvement for children post-operatively is given. Hence, a cuddly toy with integrated sensors, a plushie, is evaluated as an addition to MiRo-e with healthy children. The paper is written such that it can be read on its own without the research context. This (part I) serves as a foundation and provides some background knowledge and insights from the literary review. First, the insights of the development process of a child is provided to comprehend children's capabilities and needs. Since the study focuses on wellbeing post-operatively, pain forms a major threat. Therefore, a brief explanation of physiological signals indicative of pain in the body is given followed by tools to monitor this. Lastly, a state of the art of robotics in similar situations is provided.
The design and development steps of the plushie, tests and coding of MiRo are further in the Appendix (part III).

0.1 Development of a child

Infants, 0-1 years old, depend on their caregivers [1]. Verbalizing their needs is not within their capabilities. Hence, they use the expression of emotion as a communication tool. Initially, they cry to express their needs and as they develop, they learn to express the variety of emotions. The infant starts to be able to smile when they see the caregiver. The experiences an infant has, leads to development of emotions. However, infants are not yet self conscious of their feelings.

Toddlers, typically defined as children between the ages of 1 and 3 years old [2], undergo rapid developmental changes. During the second year of a child's life, their cognitive abilities transition from sensorimotor to pre-operational, which enables them to understand and use language and to engage in pretend play. They start to express their needs through verbal communication, including sensations as hunger and pain. In their third year, they start to verbalize their immediate circumstances. In this phase they also develop the ability to construct little stories and make real and imaginary friends. They start to be capable of identifying threats, such as recognizing a vaccination needle, based on their prior experiences. Nonetheless, they might struggle to identify more abstract dangers, like a knife, that they have never encountered before [1]. As they develop language, toddlers gain a greater sense of self, which includes the emergence of feelings of guilt and shame. Additionally, emotion regulation skills are developed during toddlerhood.

The developmental progress of preschoolers, aged 3 to 5 years old, continues at a rapid pace [1]. While 3-year-old's still struggle with tasks requiring inhibitory control and problem-solving, 5-year-old's have developed these abilities and demonstrate improved reasoning skills. Emotions start to be more complex which also results in the development of expressing and regulating their emotion. The emotional development of individuals is subject to the influence of diverse experiences and cultures, contributing to inter-individual variability [1].

Emotional development plays a significant role in how individuals experience and respond to pain. Pain is a sensory, unpleasant physical sensation. As children develop emotionally, they acquire the ability to recognize and express their feelings, including the discomfort and distress associated with pain. This growing emotional awareness allows them to communicate their pain to others and seek comfort and support. Various factors, including age, cognitive abilities, sex, previous pain experiences, temperament, cultural and familial influences, and situational factors, can modify a child's experience of pain [3]. Additionally, emotions can influence how pain is perceived and coped with, as individuals' emotional states can impact their pain tolerance, pain sensitivity, and pain-related behaviors. Therefore, this correlation is crucial for understanding behaviour of an individual when in pain which is upmost importance for pain assessment and management.

0.2 Physiological parameteres and pain

Pain is a complex physiological and neurological response that serves as a protective mechanism to alert for potential harm or tissue damage. External or internal stimuli activate receptors of the body [4]. One type of receptors are nociceptors. These respond to potentially harming stimuli and stimulate subtypes:

- mechanoreceptors
  which respond to touch, pressure, vibration and stretch
- thermoreceptors
  which respond to cold or heat
- chemoreceptors
  which respond to detect changes in chemical composition

When a receptor is activated, this causes an action potential, an electrical signal is passed along the nerves. To be exact, the signal travels through two types of afferent nerve fibers, the A-delta-type and C-type.
At a given moment, the action potential reaches the spinal cord. The two main pathways to pass the signal are the spinothalamic tract and the spinoreticular tract. The signal will reach the brain and will be processed in the somatosensory cortex. Here, the emotional and behavioural response to pain will be determined.

The autonomous nervous system (ANS) manages the involuntary functions of the body [4]. It is divided in the sympathetic and the parasympathetic nervous system. The sympathetic system is also called the fight or flight system. The parasympathetic system on the other hand is called the rest and digest system. For comparison, a few physiogical factors that are influenced by ANS are summarized in table 1.

Table 1: Based on the information of Marieb [4], the differences in a selection of physiological parameters between the parasympathetic and sympathetic nervous system.

	Sympathetic	**Parasympathetic**
Sweating	Increased	Absent or minimal
Bladder	Relaxation	Contraction
Respiratory rate	Increased	Decreased
Blood pressure	Increased	Decreased
Heart rate	Increased	Decreased
Digestion and salivation	Non-active	Active
Pupils	Dilated	Constricted
Blood flow to muscles	Increased	Minimal

Stress is an emotional and physical feeling. It is caused by unpleasant physical or mental events. Therefore, the reaction of pain on the ANS is very similar to the reaction of stress. Both stress and pain trigger the division of activity between the sympathetic and parasympathetic system in the direction of the sympathetic system. This prepares the body to respond if necessary which means that when physical reactions to stress can be measured, a relation to pain can be obtained.

Table 2: Analysis of frequently used physiological pain measures [5].

Method		Subjects	Able pain measure	Consistent across studies*	Limitations
Electroencephalogram (EEG)		Neonates, infants, CPPs, ICU patients	Yes	Moderate	Influenced by opioids, not consistently found in neonates
Cardiovascular measures	Heart rate	Neonates, infants, TBI patients, ICU/OR patients, CPPs, people with SID, healthy adults	Doubtful	No	Variable results among brain injured patients, reduced reaction in CPPs, no reaction in SID
	Heart rate variability	Neonates, infants, ICU/OR patients, healthy adults	Yes	Moderate	Inconsistent among infants in the first year of life
	Body temperature	Neonates, infants, healthy adults	Yes	Moderate	Inconsistent among healthy adults
	Blood pressure	Neonates, infants, TBI patients, OR patients, healthy adults	Doubtful	No	Blood pressure responded inconsistently to pain
Respiratory measures	Respiratory rate	Neonates, infants, TBI patients, people with SID, healthy adults	Yes	Yes	Respiratory 'irregularities' were not related to acute pain in persons with SID
	Respiratory analysis	Neonates, infants, TBI patients	Yes	Yes	Oxygen saturation was not favored for pain in neonates
Muscular measures	Muscle tension	Infants, ICU/OR patients, healthy adults	Yes	Yes	In healthy adults muscle tension response was only found with intense and prolonged pain
	Electromyogram	CPPs, healthy adults	Yes	Yes	Few studies
Electrodermal activity		TBI patients, OR patients, healthy adults	Doubtful	No	Only consistently found in healthy adults
Pupillometry		Infants, OR patients, CPPs, healthy adults	Yes	Yes	Few studies
Brain scan	MRI	CPPs, healthy adults	Yes	Yes	Different studies focused on different areas
	NIRS	Neonates, infants	No	Yes	Presence of pain on a cortical level was not found
	CBFV	Infants, CPPs, OR patients, people with SID	Yes	Yes	Few studies
	SPECT	Infants, CPPs	Yes	No	Activity varied greatly across studies
Hormonal analysis		Neonates, CPPs	Yes	Yes	Few studies
Genetics		CPPs, healthy adults	Yes	Yes	Not yet validated in large human cohorts
Automatic facial recognition		CPPs	Doubtful	Yes	Influenced by gender, age, ethnicity, movement, and lighting

Note. CPPs = chronic pain patients, ICU = intensive care unit, OR = operating room, TBI = traumatic brain injury, SID = severe intellectual disability, MRI = magnetic resonance imaging, NIRS = near-infrared spectroscopy, CBFL = cerebral blood flow velocity, PET = positron emission tomography, and SPECT = single-photon emission computer tomography. *

0.2.1 "Measuring" pain

Physiological parameters offer an alternative approach to assess pain. This is because when the body is in pain, certain physiological functions, as seen in table 1, are more or less active.

Korving et al. [5] provided methods of pain assessment by means of physiological signals that are analyzed. In this review, the invasiveness, reliability and freedom of movement are considered together with the technical maturity. The technical maturity is rated using the technology readiness levels (TRL). If the method is able to measure pain together with its limitations is displayed in table 2. In addition to this table, it must be noted that only skin conductance and facial expression recognition show a low TRL in this review.

Other interesting techniques are explored as well. One of these novel methods is photoplethysmography (PPG) [6]. With this method, the blood flow, heart rate and oxygen saturation are measured. It is a non-invasive method and often only requires a finger or wrist measurement. The volumetric change of blood is measured with the infrared

(IR) light emitted through the finger or wrist [7]. For daily use, it may be convenient to measure PPG on the forehead by including it in a head band [8]. In that way, there is relatively little motion distortion or movement restriction.
Electrocardiogram (ECG) is a method for measurements on the heart activity, including alterations in blood flow, blood pressure (BP) and body temperature. However, this requires placement of, often wired, electrodes.

In situations of acute stress, such as during or after surgery, a rapid drop in skin temperature can be observed, while core temperature tends to rise [9]. This can be measured using a simple thermometer or via a thermal camera. Use of a thermal camera, makes the technology free from body contact and allows that pain can be measured beyond the emotional experience [10].

Muscle activity is another parameter that can be measured to assess pain. Electromyography (EMG) enables the measurement of muscle tension, which increases during periods of stress or pain [9]. This also requires placement of electrodes.

As mentioned, the increase in sympathetic nervous system causes an increase in respiration rate. This causes variations in skin conductance (SC) [11]. Therefore, electrodermal activity (EDA) or Galvanic skin response (GSR) measurements can indicate stress or pain. Usually, this is measured at the fingers or palms. It was noted that the feet and shoulders are good alternatives for this followed by the forehead and wrist [12]. The forehead and wrist conductance however, do not always show a high correlation with the finger conductance [13].

Cortisol levels increase in response to stress, and although they can be measured to objectively evaluate pain responses, it is important to note that cortisol changes are subject to natural fluctuations throughout the day and can vary among individuals. As a result, cortisol measurement alone does not fully compensate for the subjectivity of pain experiences [14].

Pupil size and reflexes also undergo changes during periods of stress. Therefore, a promising method for objective pain measurement is to analyze pupil reflexes using artificial neural networks (ANN) [15].

0.2.2 Wearables

While more data might seem better, on body sensors might restrict movements of the child which could make the child uncomfortable. Additionally, the sensors could be disturbed by movements or wires could be pulled out leading to signal loss. By this means, it is essential to minimize the number of on-body sensors and cables to ensure comfort and compliance during continuous monitoring of children. Striking a balance between effective measurement and the child's comfort is crucial in this context.

Wearable sensors or wearables could provide a solution to (part of) this problem. By making sensors wearable, the patient is not or minimally restricted in their movement. In different studies, anesthetists believe that wearables could be a promising method for continuous monitoring of signals [7]. However, it was also noted that the wearables should be part of an integrated system. The monitoring should be of high quality and the hospital staff needs to be attuned to the technology.

Continuous measuring on the human body is also often used for stress detection [7]. With only a wrist worn device and an algorithm, periods of stress could be discriminated from activities requiring physical load and periods of relaxation. The wearable measures to heart activity and skin conductance to determine stress and includes an accelerometer to be able to discriminate this from physical activity. This means wearables could have a lot of potential in pain measurements as well. To start with a measuring sock for pain assessment that was developed for adults who are unable to express themselves [16]. It uses EDA and an AI-Enabled system. However, the method was only tested on healthy adults yet, the method allows to distinguish pain from no pain but does not indicate the intensity of the pain. Currently, an extreme emotional response and pain could not be separated. Nonetheless, the method seems promising.

0.3 Robotics

Novel ideas are explored to integrate robotics in healthcare since children are very willing to interact with robots [17]. Assistive robotics can be used to help with the treatment of a patient by, for example, reminding them of their medication [18]. Additionally, robots can also be used for for rehabilitation purposes. One example of this is the NAO robot, a socially assistive robot [19].

Furthermore, interactive robots are used post-operationally to reduce anxiety and increase mobilization of children [20]. Other examples show a huggable robot including sensors and response with spoken feedback [21]. The robot can be connected to a PC on which games can be played with comprehending software via radio connection. This combination of a robotics toy with games is used in other research as well. For the robot SenToy, the emotions in the game are influenced by the sensor input of the toy [22]. This means the robot is the interface to the game. It includes accelerometers, analog position meters to measure the position of the limbs and digital sensors to measure if the eyes are on the hands or not. The doll can capture emotions from the gestures.

In research using robotics for emotional support, the robot, Huggable, was designed to interact within hospital environment [23]. It includes 12 degrees of freedom (DoF) and multiple sensors including pressure sensors in the paws. These sensors were designed with the idea that children, who are unable to verbally express themselves, can squeeze the paws when they experience pain. It was seen that the children, especially ill children, physically interacted with the robot.

To sense and react to emotions, tangible robot Pepita was designed [24]. Since body contact is very important for emotional expressions, the robot can sense touch and transcribe this to certain feelings. Pepita projects visuals as a response to the affective information it senses. Sensing touch can be done by covering the robot with pressure sensors. Pepita also has Hall-effect sensors to measure the stretch of the robot. Together, the sensors contributions are the input of a a hug detection method. Which computes if Pepita is hugged or not.

Using robotics for hospitalized children could help to tackle undertreatment. As an example, social robotics has the potential to reduce the communication barrier between hospital staff and child [25]. Children tend to have a personal relationship with robots and share personal information. Therefore, robots can be used to obtain information about the user's wellbeing [17]. To be able to capture an accurate representation of the wellbeing of the child, the child should have interaction with the robot. However, the human-robot interaction (HRI) differs per child [26]. The amount and intensity of the interaction could be increased by, for example, personalization of the robot since appearance influences the amount of interaction.
Using AI, robots can learn how to react in the desired manner in a variety of situations which could lead to improved contact between the child and the robot. With Machine learning (ML), the data that the robot can store can be used for classification and automated interpretation [27]. These techniques were used in an idea to use facial analysis for pain assessment of patients with dementia [28]. The electronic pain assessment tool (ePAT) recognizes the facial expression of patients to discover emotions.

References

[1] V LoBue ea. Handbook of Emotional Development. Springer International Publishing; 2019.

[2] Colson ER, Dworkin PH. Toddler Development. Pediatrics in Review. 1997;18:255-9.

[3] Walco GA, Goldschneider KR. Pain in children: A practical guide for primary care. Humana Press; 2008.

[4] Marieb EN, Hoehn K, Hoehn M. Global edition Human anatomy Physiology tentH edition Human anatomy Physiology; 2016.

[5] Korving H, Sterkenburg PS, Barakova EI, Feijs LMG. Physiological Measures of Acute and Chronic Pain within Different Subject Groups: A Systematic Review. Pain Research and Management. 2020;2020.

[6] Argüello-Prada EJ, Valencia RDM. On the use of indexes derived from photoplethysmographic (PPG) signals for postoperative pain assessment: A narrative review. Biomedical Signal Processing and Control. 2023;80:1746-8094. Available from: https://doi.org/10.1016/j.bspc.2022.104335.

[7] Can YS, Chalabianloo N, Ekiz D, Ersoy C. Continuous stress detection using wearable sensors in real life: Algorithmic programming contest case study. Sensors (Switzerland). 2019 4;19.

[8] Kim SH, Ryoo DW, Bae C. Adaptive Noise Cancellation Using Accelerometers for the PPG Signal from Forehead. Proceedings of the 29th Annual International. 2007:2564-7.

[9] Chen J, Abbod M, Shieh JS. Pain and Stress Detection Using Wearable Sensors and Devices—A Review. Sensors 2021, Vol 21, Page 1030. 2021 2;21:1030. Available from: https://www.mdpi.com/1424-8220/21/4/1030/htmhttps://www.mdpi.com/1424-8220/21/4/1030.

[10] Erel VK, Özkan HS. Thermal camera as a pain monitor. Journal of Pain Research. 2017;10:2827-32. Cited By :3. Available from: www.scopus.com.

[11] Sugimine S, Saito S, Takazawa T. Normalized skin conductance level could differentiate physical pain stimuli from other sympathetic stimuli. Scientific Reports 2020 10:1. 2020 7;10:1-12. Available from: https://www.nature.com/articles/s41598-020-67936-0.

[12] van Dooren M, de Vries JJGGJ, Janssen JH. Emotional sweating across the body: Comparing 16 different skin conductance measurement locations. Physiology and Behavior. 2012 5;106:298-304.

[13] Hossain MB, Kong Y, Posada-Quintero HF, Chon KH. Comparison of Electrodermal Activity from Multiple Body Locations Based on Standard EDA Indices' Quality and Robustness against Motion Artifact. Sensors. 2022 5;22.

[14] da Cruz Rebelato CT, Stumm EMF. Analysis of pain and free cortisol of newborns in intensive therapy with therapeutic procedures. BrJP. 2019 6;2:159-65. Available from: https://www.scielo.br/j/brjp/a/zwSCr8dvwJJhcVtrtMDSJvh/?lang=en&format=html.

[15] Wang L, Guo Y, Dalip B, Xiao Y, Urman RD, Lin Y. An experimental study of objective pain measurement using pupillary response based on genetic algorithm and artificial neural network. Applied Intelligence. 2022 1;52:1145-56.

[16] Korving H, Zhou D, Xiang H, Sterkenburg P, Markopoulos P, Barakova E. Development of an AI-Enabled System for Pain Monitoring Using Skin Conductance Sensoring in Socks. International Journal of Neural Systems. 2022 10;32.

[17] Kory-Westlund JM. Implications of children's social, emotional, and relational interactions with robots for human–robot empathy. Routledge; 2023.

[18] Lamberts V, Drossaert CHC, Spook JE, Robotics R, Papenburg BJ. "Hé James" A study on the use of a social assistive humanoid robot in paediatric patients during post-operative tonsillectomy treatments;.

[19] Mccarthy C, Butchart J, George M, Kerr D, Kingsley H, Scheinberg AM, et al. Robots in Rehab: Towards socially assistive robots for paediatric rehabilitation. 2015. Available from: http://dx.doi.org/10.1145/2838739.2838791.

[20] Topçu SY, Semerci R, Kostak MA, Özlem Güray, Sert S, Yavuz G. The effect of an interactive robot on children's post-operative anxiety, mobilization, and parents' satisfaction; randomized controlled study. Journal of Pediatric Nursing. 2023 1;68:e50-7.

[21] Luckin R, Connolly D, Plowman L, Airey S. Children's interactions with interactive toy technology. Journal of Computer Assisted Learning. 2003;19:165-76.

[22] Paiva A, Costa M, Chaves R, Piedade M, Mourão D, Sobral D, et al. SenToy: an affective sympathetic interface. International Journal of Human-Computer Studies. 2003 7;59:227-35.

[23] Jeong S, Santos KD, Graca S, O'Connell B, Anderson L, Stenquist N, et al. Designing a socially assistive robot for pediatric care. Association for Computing Machinery, Inc; 2015. p. 387-90.

[24] Nunez E, Hirokawa M, Suzuki K. Design of a Huggable Social Robot with Affective Expressions Using Projected Images. Applied Sciences 2018, Vol 8, Page 2298. 2018 11;8:2298. Available from: https://www.mdpi.com/2076-3417/8/11/2298/htmhttps://www.mdpi.com/2076-3417/8/11/2298.

[25] Ferrari OI, Zhang F, Braam AA, van Gurp JAM, Broz F, Barakova EI. Design of Child-robot Interactions for Comfort and Distraction from Post-operative Pain and Distress. Association for Computing Machinery (ACM); 2023. p. 686-90.

[26] Ferrari OI, Zhang F, Braam AA, van Gurp JAM, Broz F, Barakova EI. Design of Child-robot Interactions for Comfort and Distraction from Post-operative Pain and Distress. Association for Computing Machinery (ACM); 2023. p. 686-90.

[27] Mlakar I, Smrke U, Flis V, Bergauer A, Kobilica N, Kampič T, et al. A randomized controlled trial for evaluating the impact of integrating a computerized clinical decision support system and a socially assistive humanoid robot into grand rounds during pre/post-operative care. Digital Health. 2022;8.

[28] Hoti K, Atee M, Hughes JD. Clinimetric properties of the electronic pain assessment tool (ePAT) for aged-care residents with moderate to severe dementia. Journal of Pain Research. 2018 6;11:1037-44.

The power of play

Exploring interactions with a plushie enhanced with sensors and a responsive robot as a tool for assessing and improving child wellbeing post-operatively

Abstract
In hospital settings, surgeries impact a child's wellbeing physically and emotionally. Potential stress of the situation and the limited communication can cause anxiety, loneliness and undertreated pain. Young children do less often get adequate treatment compared to adults, while undertreated pain can increase and lengthen the duration of symptoms. Therefore, assessing and improving the wellbeing of hospitalised children is very important. For this purpose, a plushie resembling a magic wand, enhanced with a microphone, an Inertial Measurement Unit (IMU), capacity pads and a pressure sensor, is developed as a new tool for interaction with robot MiRo-e while being indicative of and enhancing the wellbeing of preschoolers. Promising results were obtained from tests evaluating the plushie and robot conducted with six healthy participants (ages 4-5.5), showing the technology's potential to offer companionship and distraction and indicate the child's wellbeing. After further improvements and tests, the system could be implemented in clinical settings to assess the wellbeing of children post-operatively to tackle undertreatment and improve their wellbeing by providing companionship and personalised distractions.
Keywords: child-robot interaction, pain management for children, robotics in healthcare

Danique Damen, February 26, 2024

1 Introduction

Following the Cambridge dictionary, *"Wellbeing is the state of feeling healthy and happy"* [1]. This includes a physical, emotional and cognitive aspect. Optimising a child's wellbeing is crucial for its development and prospects, which is especially important to safeguard. Nevertheless, there are situations when this cannot be avoided, as children might experience stressful circumstances such as receiving medical care in a hospital. Children often struggle to comprehend the problem as they have not experienced anything like this before. There is usually a lack of communication explaining the situation towards the child, known as the communication barrier [2]. Children are a vulnerable target group in their developing phase, where they might be limited in their verbal, cognitive and emotional abilities. As a result, children undergoing hospitalisation often experience discomfort [3], anxiety and loneliness [4]. This emotional ballast, combined with the physical pain, significantly impacts their overall wellbeing. Consequently, it was observed that children less often get adequate treatment, including medication, compared to adults [3]

1.1 HELPER project

This research is part of a larger project which intends to use robots for pain management in children [5]. For this purpose, the University of Twente started the Hospital Environment Linked Pain Evaluation Robot (HELPER) project [6]. HELPER aims to evaluate and enhance a child's wellbeing after surgery by analysis of the child's interaction with a social robot alongside physiological measurements. This could be particularly beneficial for toddlers who cannot verbally express themselves but can comprehend instructions and participate in play.

Utilising a robot for this objective presents several advantages. Firstly, children show interest in robots and are very well-willed to build a trusting relationship [7]. Hence, robotics have the potential to provide companionship and distraction, thereby providing a valuable tool to tackle the communication barrier between hospital staff and the child that could cause undertreatment [2].

Therefore, robot MiRo, as seen in figure 1, is implemented for this purpose [2]. This commercially available robot is chosen for its zoomorphic design and various functionalities [8]. In appendix G, the robot and its functionalities are described in more detail.

Figure 1: The MiRo-e robot is used in the HELPER project for research purposes [8].

It is noted that MiRo offered the potential to alleviate a child's distress in a hospital setting [8]. This contributes to the improvement of their wellbeing. However, it must be noted that the design of MiRo offers a lot of potential regarding its kinematics but lacks cuddliness. Notably, prior research of Huggable [9] and Pepita [10] highlighted that physical interaction could increase the emotional wellbeing of a child and squeezing can help control pain [11].

In previously conducted research with MiRo, customisation of the robot and the value of history between child and robot was investigated [12]. Customisation was achieved through a combination of game-based design and co-design. A connection between robot and child was created through an interactive superhero story. The appearance of MiRo was the topic of other research as well [13]. However, this also incorporated the addition of wearables. The wearables would be used for the physiological assessment of the child. The primary focus was the design of the wearables. Other research focused on the added value of physiological data for pain assessment [14]. Using the skin conductance shows potential as an indicator for pain assessment [15].

Thus, MiRo can be used to improve wellbeing and combinations with wearables are being investigated. Nonetheless, a representation of the child's wellbeing has not yet been captured. Wellbeing can be assessed with the assessment tools giving a snapshot of the situation by the hospital staff.

1.2 Goal

Consequently, this study aims to explore the combination of wellbeing enhancement and assessment of the child's wellbeing. As wellbeing is currently being assessed with behavioural parameters, the feasibility of partially automating this assessment using sensors is explored.

Although MiRo lacks cuddliness, children seek comfort from hugging their toys [10]. As noted in [12], previous feedback from children expressed the desire for a tangible extension to enhance the robot. Consequently, this research introduces a plushie toy as an accessory to MiRo. This also brings possibilities. This research aims to create a tool for measuring the child's behaviour by incorporating sensors into the plushie. This could indicate the child's wellbeing while encompassing actions like hugging, squeezing and shaking. This provides a novel method to explore the power of play while obtaining data from the child.

As a contribution to the HELPER project, this study aims to investigate the robot's potential with plushie combination as a tool for wellbeing improvement and assessment. Thus, the research question and subquestions are defined as:

> "*How can a plushie enhanced with a microphone, an IMU, capacity pads, and a pressure sensor contribute to improving and assessing a child's wellbeing?*"

1. To what extent do the test subjects of the 3-5-year-old group understand the interaction possibilities with the plushie and the corresponding reactions of the robot?
2. To what degree can a child's behaviour be captured with the sensors integrated into the plushie?
   2.1 To what extent can this captured data be translated into meaningful indicators of the child's wellbeing?
3. Is the plushie a valuable addition to the robot for improving the wellbeing of the test subject?
   3.1 Does the plushie enhance the user experience with the robot?

1.3 Hypotheses

As the technology is developed for this specific purpose, children within the designated age range comprehend the potentialities of interaction associated with the plushie, which leads to the robot's responses.
The physical interactions and enhanced potential for distraction and entertainment lead to an increased connection of the child with the robot and an improved user experience, contributing to the enhancement of the child's wellbeing.
The integrated sensors capture the intensity and frequency of interactions induced by the child, which represent the behaviour of a child and thus give meaningful indications of the child's wellbeing.

These hypotheses all contribute to the hypothesis of the primary research question. The plushie, integrated with a microphone, an IMU, capacity pads and a pressure sensor, will enhance and assess the wellbeing of 3-5-year-old children.

2 Background information

For hospitalised children, understanding and effectively managing pain is crucial for optimising their wellbeing. This chapter presents background knowledge regarding pain and pain assessment tools to comprehend the current situation.

2.1 Pain

Pain is a prevalent symptom following surgery. However, it forms a significant risk to the child's overall wellbeing. The brain processes the pain stimuli to determine the behavioural and emotional response to pain. The mental state of the child can influence the perception of pain. Anxiety, for example, can increase the intensity of the pain feeling. Therefore, the signal that flows through the nerves is not directly linked to pain intensity. Improving the mental wellbeing of the child could lead to feeling less pain [16].

The symptoms of pain in children vary from that of adults. Examples of potential symptoms are crying, screaming, anxiety, physical resistance, certain facial expressions, alertness, calmness, movement, how much they play, worrying, eating less or more, being quieter, holding the sore part of the body and groaning or moan more than usual [17].

Due to their development process, children might lack experience with pain. Indicating the intensity of pain verbally or in another way might be difficult. However, undertreated pain could lead to an instantaneous or ongoing increase of pain[18], a longer recovery period [19], anxiety [20] and can affect the child on the long-term [3]. Since monitoring pain could contribute to the prevention of undertreatment, it could be an effective tool for safeguarding the wellbeing of a child post-operatively.

2.2 Pain assessment tools

Post-operative pain is very common. However, the scope of post-operative pain experienced by children tends to be more narrow compared to adults [18]. To effectively monitor the post-operative well-being of children, it is important to understand the current tools.
Current pain assessment tools mainly depend on self-report, as it is considered the golden standard [3] [21] [22]. Nevertheless, certain limitations are associated with self-reporting, especially for children under five years old [3]. Given their rapid development, these young children may encounter difficulties in accurately expressing their experiences of pain. One approach to tackle this challenge is having parents assess the intensity of their child's pain. It has been observed that such assessments do not consistently align with the child's indications [23]. Therefore, pain assessment in this age group remains a significant challenge.

Thus, this research specifically targets preschoolers (children aged 3-5) since they find difficulty in verbal communication, but behavioural symptoms indicative of pain can be observed.

Various postoperative pain assessment tools have been developed that focus on observing the child's behaviour [19]. Based on this review, the most appropriate pain scales for this age group are the Children's Hospital of Eastern Ontario Pain Scale (CHEOPS) and the Face, Legs, Activity, Cry and Consolability (FLACC). In short, the tools take crying, facial expression, verbal communication or consolability, and activity of the legs, torso and arms. The tools are further explained in appendix A.

However, despite their usefulness, these tools have several limitations that must be considered. The developmental differences among children can significantly influence their pain response, making it challenging to generalise the findings across different age groups and individual children. Secondly, healthcare providers often face time constraints and work pressure, which may limit their ability to thoroughly observe a child's behaviour and capture an accurate representation of their pain experience during the observation time. Furthermore, children may feel the need to please adults or may have fears related to medical procedures, leading them to downplay or deny their pain [20]. Distractions during medical procedures or adaptation of the child can also misrepresent the situation. Lastly, children might behave differently, which could lead to misinterpretation of behavioural cues [24].

3 Research design

3.1 Development

To achieve the goal set, a plushie is designed. Based on the behavioural assessment tools, sensors are chosen as described in section 3. A microphone is included to capture the crying and verbal statements of the child. Furthermore, a balloon with an attached air pressure sensor is included to measure squeezing and hugging as seen in robot Pepita [10]. Additionally, an Inertial Measurement Unit (IMU) is used to capture movements of the plushie and, therefore, capture, for example, throwing and shaking. Lastly, a capacity sensor measures whether the child is holding the plushie. Together, this data forms a representation of the interaction the child has with the plushie. The plushie is prototyped as a magic wand, as seen in figure 2. In appendix D, a more detailed walk-through of the development stages of the plushie is provided. Initially, the researcher conducts tests with the magic wand and robot separately before proceeding to the actual tests with children. The data collected during tests serve as a basis for comparison.

Figure 2: MiRo-e with the magic wand prototype of the plushie

To keep the child's interest, MiRo should respond to the interactions with the magic wand induced by the child. Therefore, data transmission from the plushie to MiRo is established with Bluetooth Low Energy (BLE). The robot reacts with moves and audio, as documented in appendix G.

As seen in figure 3, three test phases are developed to investigate a child's reactions and interactions with the technology.

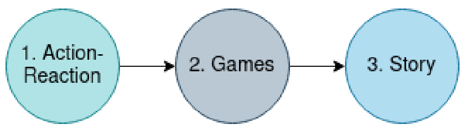


Figure 3: The test with MiRo and the plushie consists of three phases: exploring the reactions consequent to actions, one of the three games and a story.

The first phase is designed to let the child explore the interaction possibilities. With this, the child has to induce reactions and thus, their understanding can be analysed. MiRo responds to high sounds, shaking, squeezing and holding with audio, movements and lights.

Since one of the goals is to increase a child's wellbeing, the technology should at least offer distraction. Therefore, **the second phase** explores the power of play. The child can choose one of three different games. Namely, a dance party, guessing the animal sound and Simon Says. From this, an attempt to combine capturing the behaviour of the child while they are having fun is made.

If the child is more hesitant, they might not feel fully comfortable participating actively in a game. Therefore, a different approach for a fun distraction is used as well. Namely, an interactive story about the history of MiRo and the magic wand can be played in **phase three**.
Appendix F gives a more elaborate description of the phases.

3.2 Participants

As this is an exploration study, it was chosen to do pilot tests with healthy children. A small sample size is of limited importance. The test focuses on documenting and observing the child's reactions to test the hypothesis stated. This data explores the relationship between the interactions and a child's behaviour. Then, potential relations to a child's wellbeing are investigated with the current wellbeing assessment tool as stated in appendix A.

The participants were recruited at the daycare at the University of Twente de Vlinder. The inclusion criteria of the tests are children between 3 and 5 years old who are Dutch-speaking and who are, as far as known, mentally and physically healthy. The participant's parents or guardians were informed and consented via the briefing, which can be read in appendix F4. The pronouns that will be used for each child are "they/them".

3.3 Setting

The tests are done at the daycare location to make it as convenient as possible. A separate room attached to the living room is utilised. However, this room has no door, which makes it a tumultuous environment. MiRo is set up on a table and a chair is put in front of it, facing the door. The researchers took place on the right and left sides of the table.

3.4 Procedure

Before the child is seated for the experiments, the child is greeted when they walk into the room. They are introduced to the researchers and the robot. After taking a seat, the child is told that MiRo is "sleeping", waiting for the plushie to connect to start. They are given the magic wand with the question of whether they can wake MiRo using a magical spell. It takes six seconds after the terminal command for the plushie to connect and an additional three seconds for MiRo to "wake" and to start its introduction.

In principle, the child follows the order of the phases as described in section 3.1. They get to skip a phase or switch the order of the phases. After every phase, MiRo asks the child if it wants to continue. Additionally, the pedagogical scientist monitors the child's comfort level throughout the experiment and the researcher and child can decide to quit anytime.

Since the experiment is relatively short, the mean of each sensor during the experiment is calculated to combine the frequency and intensity of the child's interactions with the plushie. With this, variability during the experiment is smoothed, noise is suppressed and a summary of the longer period is given, making interpretation of the data easier. Furthermore, the observations of the pedagogical scientist according to the observation tool are stated in appendix H.

4 Results

Six children meet the inclusion criteria and are recruited to participate. The data from the sensors is processed and displayed. Additionally, the notes on the child's behaviour are transcribed to form profile sketches.

4.1 Sensor data

Each child's data from each sensor is visualised to analyse the interactions at specific parts of the tests.

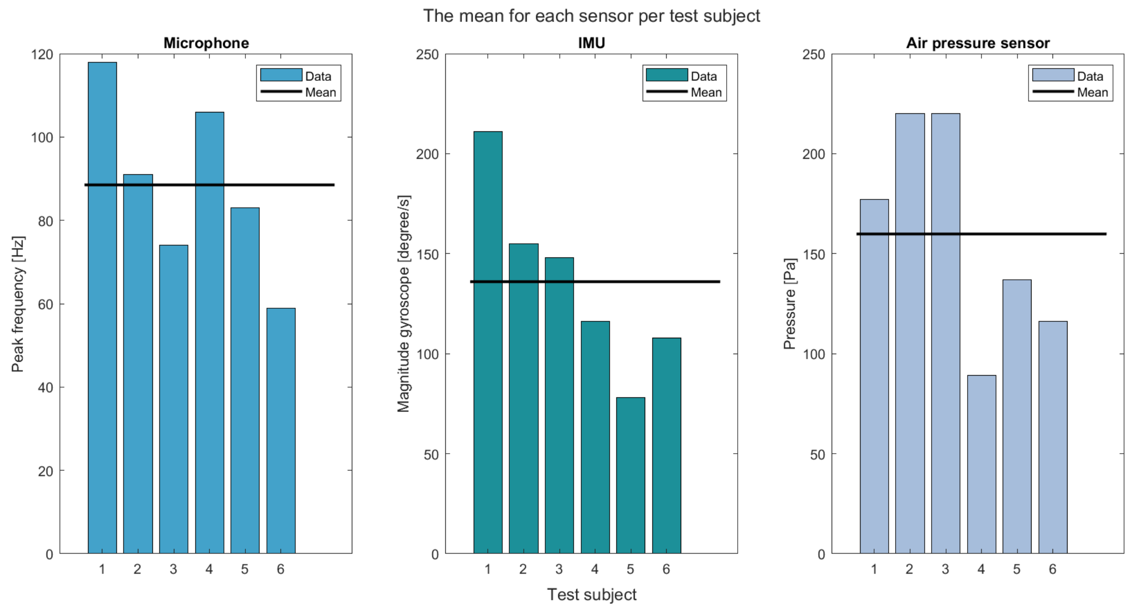


Figure 4: The mean for the microphone, IMU and Air pressure sensor per test subject.

The number of interactions and the mean for the interactions per sensor are derived. The graphs of the sensor data against time and the peaks and intensity of interactions are included in appendix I.

For test person one, fewer microphone peaks are observed, meaning the child talked less than average. Additionally, the number of peaks and the mean of the angular velocity and pressure sensor are smaller, meaning the child moved and squeezed the plushie fewer times and less intensely than average. This could indicate the child is less engaging with the technology than average.

Test person two interacted most standard with the plushie. The number of interactions measured with the microphone and IMU are average, as well as the intensity of the interactions with the IMU and pressure sensor. The number of interactions with the capacity and pressure sensors is above average. Thus, the dynamic behaviour of the child is not exceptional.

For test person three, more microphone and capacity sensor peaks are observed. Additionally, the mean of the pressure applied is above average, meaning the child is squeezed with more power. The intensity of the microphone and IMU are below average. Overall, the child squeezed harder but moved with less intensity. Thus, a one-sided statement of its interactive behaviour is hard to make.

The mean of the magnitude is larger for test person four, meaning its movements are more intense. However, the number of peaks for the IMU, capacity sensor and pressure sensor are below average, meaning there was less interaction. Additionally, the mean of the pressure applied is smaller.

Test person five chose to skip the games. During the self-exploration phase and the story, the child interacted very moderately. The number of interactions is smaller for the microphone, capacity sensor and pressure sensor but larger for the IMU. Therefore, during these phases, the child moved the plushie more than average. However, these interactions were less intense than common. The intensity of squeezing is close to average. Overall, the child seems to interact slightly less and less intensely than average.

Fewer interactions were measured for test person six, except for the capacity sensor. The intensity measured with the microphone and pressure sensor is above average. However, the child moved the plushie with less velocity.

No clear patterns of interaction amount and intensity are obtained since little intra-individual variability is observed. Therefore, the mean of the measurements for each sensor during the entire experiment is calculated and displayed in figure 4 for each test person to combine the intensity and frequency of the interactions. Since the capacity sensor does not measure intensity but only if the sensor is touched, these are not displayed. The lack of baseline or reference data makes this derivation important for analysis.

Subsequently, the deviations from the mean of the test group are provided in table 1. If the percentage is positive, the child interacted more with the sensor on average than the mean of the test group. The percentages equally contribute to the combined percentage to create one value representing the amount and intensity of interaction compared to the mean.

Table 1: The deviations from the mean of all children during the tests for the peak frequency (Mic = 88.5 Hz), magnitude of the gyroscope (IMU = 136°/s) and air pressure sensor (Air = 159.83 Pa) and its mean per test person.

Test person	Deviation from mean [%] Mic	IMU	Air	Mean [%]
1	33.33	55.15	10.74	33
2	2.82	13.97	37.64	18
3	-16.38	8.82	37.64	10
4	19.77	-14.71	-44.32	-13
5	-6.21	-42.65	-14.29	-21
6	-33.3	-20.59	-27.42	-30

It can be noticed that the mean of the measurements for test persons one and two are above average for each sensor. This is the case for one or two sensors for test persons three and four. For test persons five and six, the mean for each sensor is below average.

4.2 Observations

The profile sketches of the individuals are derived from the transcription of the notes taken during the tests and provided in appendix J. These are summarised in two key characteristics for simplification, as stated in table 2.

In general, the children looked excited to start playing. They were well-willed to participate and obeyed the commands given. This entails that they kept sitting in their chair and did not touch MiRo, even though this was not mentioned during instruction. They wondered while MiRo reacted to the magic wand. Compliments from MiRo were received with gloating and smiles.

Table 2: Outstanding characteristics of the profiles of the test persons.

Test person	Characteristics	age (years)
1	Enthusiastic and energetic	5.5
2	Clever and chatty	5.5
3	Calm and reserved	5
4	Humoristic but focused	4
5	Expectant and shy	4.5
6	Amazed but expectant	4.5

5 Discussion

The discussion is divided into interpreting the results, section 5.1, and the study's limitations, section 5.2.

5.1 Interpretation results

The parameters used to measure the child's interactions with the plushie provide valuable insights. Variability of the peak frequency of a child can be analysed to discriminate emotions or crying. Therefore, while inter-individual differences between these tests are negligible, resulting in only small relevance, the concept should be considered for testing during longer observation periods.

With the IMU, the angular velocity is measured and the corresponding magnitude is calculated. This provides insights into the intensity with which the child moves the plushie. Elevation of this magnitude signifies more intense engagement of the child with the plushie.
The capacity sensor detects if the plushie is held, a fundamental but simple interaction. More peaks indicate that the plushie is held more. During these tests, the child constantly holds the plushie, making the measurements not most important. For longer observation periods in which interaction is not always demanded, this could indicate engagement or cuddling for comfort.

The results are further interpreted and discussed in the order of the calculations. First, the interaction peaks and intensity are described, followed by the deviations from the mean to conclude with the linkage of the data to the observations of the behaviour of the test persons.

5.1.1 Peaks and intensity

From this data, some general observations are noteworthy. The capacity sensor does not function properly. During the tests, each test subject constantly held the plushie, which should be represented in the data. However, the plushie is not entirely covered with capacity pads, which could lead to undetected holding. This is further discussed in the prototype evaluation K. As a consequence of this issue and the continuous holding of the plushie, the data from the capacity pads is taken into account but not considered crucial for exploration for indications of the child's behaviour.

Although the relevant pressure measured represents the intensity of squeezing a child, the measured value is not the actual force applied since it also depends on other factors. A higher mean pressure signifies more force, a more intense interaction. Squeezing can be used for pain management or emotional expression. Therefore, the intensity of the pressure can be considered a meaningful parameter for analysis.

The amount of data points is not continuous but relatively low. The period between saving data varies due to the code structure. The discussion of the software, including this issue, is elaborated in appendix K. Measurements are saved approximately every four seconds. This is very long and leads to missing interactions in the data log. Consequently, crucial information can be missing during the interpretation of the data, with deviating conclusions as a consequence.

5.1.2 Deviations from the mean

The mean value of each sensor over time during the test is calculated. In that way, the frequency and intensity of interactions are combined in one value for each sensor. From this data, it can noticed that test persons one and two are interacting above average according to each sensor. Test persons three and four are close to average, and five and six are interacting below average. This is not completely in line with the intensity per interaction for each analysed child. For example, test person one interacted less often and was less intense with the plushie than average, but they seem most interactive from this data.

However, it is already noted that the separate data is complex to analyse, meaning that different conclusions could be drawn when combined. The interactive behaviour of each child is easier to compare, but important information could be lost when this combination is used. The value could be unrepresentative of the actual interactive behaviour. Further investigation should explore the consequences of the calculation steps.

In the current calculation, the peak frequency is considered equally important to the interaction value as pressure and angular velocity. This impacts the relevance of this value significantly since, as already noted, inter-individual differences in peak frequency are not that relevant, contrary to intra-individual differences, since each child's voice has its frequency, which can not be used to compare behaviour.

Additionally, the standard error of the mean is not considered in the analysis. After each calculation, the error increases, affecting the values' reliability.

Lastly, the mean of the sensor data is calculated with the time of the test. However, the duration of the test varied by causes, including the speed of understanding the commands. Additionally, the number of commands is not increased when the test duration is more prolonged. This leads to a more minor frequency of commands, meaning fewer interactions from the technology, which most likely results in less frequent interactions with the child. Therefore, the reliability of the value stated as an indicator of interactive behaviour is questionable.

Comparing the results from the deviation to the mean and the number and intensity of interactions, the conclusions match except for test person one. It is hard to tell which conclusion is correct since combining data could lead to a better representation of the overall behaviour or misleading conclusions due to information loss.

5.1.3 Observations

In general, the child seemed interested in the robot. They paid close attention to MiRo's instructions and obeyed its commands quickly. They used the magic wand to interact with MiRo instead of touching the robot, even though this was not verbally instructed. Therefore, using the plushie for interactions seems natural for the children. However, test person three did not seem confident in their interactions since they were looking at the researchers for confirmation. Test persons five and six did not always seem to hear or understand the commands of MiRo. Since the test duration is relatively short, the instructions from the researchers are fairly minimal, and no history is created between the child and the robot; this is not a reason for concern. After some hints, the children did understand what to do. This is reason to believe that after implementing the technology as devised, the confidence and understanding of these children is improved to the desired level.

Hypothetically, as stated in section 1.3, the intensity and frequency of interactions can represent a child's behaviour. Therefore, the child's interactive behaviour should match the child's profile sketch during the test. From the profile sketches, it can be noticed that test persons one and two are more energetic and actively engaging than average. Test persons five and six seemed more shy and expectant with the technology. The amount and intensity of interactions of test persons three and four can be considered between these groups.

Considering the combined deviation from the mean of the interactions of the test persons, this matches precisely. Therefore, the sensor data can indeed be considered indicative of the children's behaviour. However, this can not be directly read from the amount and intensity of the interactions. After improving and enhancing the technology and sensors, this relationship should be further investigated. Additionally, the intra-individual variability in behaviour is neglected in this research regardless of its significant importance in capturing the child's behaviour. This variability is too small during this experiment to provide valuable insights.

For future research, the investigation of the variability of each individual and the relations to the changes in wellbeing should be explored. As stated, changes in a child's wellbeing are reflected by changes in their behaviour. The current matches between the profile and deviation to the mean show potential for capturing the interactive behaviour of the child and thus for wellbeing assessment.

Using a plushie to measure the interactive behaviour of a child is very different from current wellbeing assessment methods. Matching the measurements to the profile sketches shows potential for measuring intra-individual changes in behaviour and, thus, in wellbeing. Each child behaves differently and reacts differently to physical and emotional stress. Therefore, creating a baseline of data through the pre-operative history of MiRo and the child allows for documenting the changes of each individual. The current most used tools for pain assessment, as stated in appendix A, give only a snapshot of the situation and score each child on the same parameters. With this, the inter-individual variability is not respected carefully. Therefore, the plushie shows great potential to enhance the current method.

Many parameters of current assessment tools can be measured using the sensors of the plushie. Crying and the child's verbal expressions can be measured using the microphone, discriminated, and analysed with further data processing. The consolability of a child can be measured when the robot tries to comfort the child. Additionally, a child's activity can be measured using the amount and intensity of the child's interactions. Since this is a new approach to investigating the child's wellbeing, it is not a direct replacement for the current tool. However, this could also provide new, complementary indicators of the child's wellbeing. Therefore, the technology offers potential for wellbeing assessment but should be further developed and explored.

The technology is not only designed as a functional tool. The robot and plushie could provide the child companionship, distraction and comfort. From the tests, it can be noted that the children enjoyed playing with the technology. The children all seemed to enjoy playing with the robot. A lot of smiles were observed. They got motivated and happy when receiving positive feedback from the robot. As a specific example, it is noted that test person six did not talk to the staff in the daycare. Nonetheless, she did seem to enjoy playing with the technology and participated. Thus, the technology can help to tackle the communication barrier between staff and children. Previous research with only the robot already showed that it can be used as a tool for wellbeing enhancement [2]. No distinction is made during the tests with only the robot or the combination with the plushie. However, the children seemed to enjoy physically interacting with the plushie, which could provide comfort in stressful situations [10]. The enthusiasm with which they played with it made it look like a tangible extension to MiRo, which is an excellent addition to the previous setup. Additionally, the robot brings many possibilities to bring joy and companionship. It allows personalisation and choosing preferred distractions.

5.2 Limitations

Before conclusions of the findings can be drawn, it is essential to acknowledge the study's limitations. In this section, the limitations encountered are categorised as limitations of the methodology, plushie, and experiment.

5.2.1 Methodology

The present methodology may not be most optimal for evaluating the hypothesis set, as stated in section 1.3. Limitations and possibilities for improvement and enhancement of the developed plushie are elaborated in appendix K. Noteworthy is that it is crucial to increase the frequency of interaction assessments to provide a more continuous and reliable overview of the interactive behaviour of the child.

Furthermore, the age range of the recruited test subjects is between 4 and 5.5 years, deviating from the broader target group. Consequently, conclusions drawn, especially regarding younger children's understanding of the technology, need to be approached with caveat.

The current test does not accurately reflect the situation for hospitalised children. The relatively short duration makes it challenging to capture intra-individual variability effectively. Furthermore, the test is designed for constant interaction of the child, whereas in a hospital setting, the child can choose to interact whenever they desire, providing additional valuable insights. Consequently, the current method is limited in its ability to capture changes in a child's behaviour. Recommendations on improvement are provided in section 7.

Subsequently, accurately translating a child's behaviour to indicators of wellbeing is also limited. Currently, there is no baseline for the data. There is already a lot of variability between children when they feel well, let alone their responses to pain. Therefore, creating a baseline for each individual and analysing the intra-individual variability is very important. Creating a pre-operative history [12] can contribute to this purpose.

With the current method, it is hard to state if the plushie is a valuable addition to the robot since there is no reference material with only the robot. However, the user experience with the system can be evaluated.

5.2.2 Experimental setup

Given the exploratory nature of this research, it is of limited importance for this scope that the sample size is small, with only 6 participants. Despite that, it must be recognised that these participants do not comprehensively represent the entire target group. Additionally, all test persons were recruited at the same daycare, which could mean there are correlations regarding their behaviour.

Additionally, the current test setup is very different from a hospital setting. The tests were executed in an open room, which could mean the sensor data is disturbed by noise.

6 Conclusion

The interactions of children (aged 3-5) with a plushie and MiRo are explored using play. Despite limitations in the methodology, valuable insights are obtained of the potential of the technology for wellbeing assessment and enhancement for children post-operatively.

6.1 Sub-question 1

Matching the hypothesis stated in section 1.3, the test subjects quickly understood the technology. After exploring the plushie's possibilities, they understood that the interactions induce MiRo's actions. Nevertheless, there are specific improvement suggestions to optimise the understanding and confidence of the children with the technology elaborated in section 7.

6.2 Sub-question 2

The sensor data from the plushie offers indications of the child's behaviour. The measurements of the interactions with the plushie can be linked to the profile sketch of the child. The limitations of the test method regarding intra-individual variability and the lack of baseline data must be acknowledged and further explored. Nevertheless, the potential of the plushie to provide indications of the child's behaviour is in line with the hypothesis.

6.3 Sub-question 3

The positive user experience with the plushie highlights the value of the plushie as an enhancement to the robot for improving the wellbeing of children. The enthusiasm and engagement observed highlight the potential of the plushie to provide an opportunity for physical interaction, allowing entertainment, distraction and companionship.

6.4 Main research question

In this exploration research, the plushie enhanced with a microphone, an Inertial Measurement Unit (IMU), capacity pads and a pressure sensor shows promising potential for addressing the wellbeing of 3-5-year-old children in a novel and playful manner. This can be interpreted from the conclusions of the sub-questions, addressing the understanding of the technology, capturing the behaviour and enhancing the overall wellbeing of the test persons. To conclude, the plushie could contribute to the HELPER project to tackle the undertreatment of hospitalised children and provide companionship, comfort and distractions.

7 Recommendations

This research shows that combining the robot with a plushie shows potential for wellbeing enhancement and assessment. However, before implementing the technology, it should be improved and tested clinically with a greater sample size. Additionally, there are many possibilities for enhancing the technology, which could result in more accurate results.

7.1 Testing

Since this is an exploration research, the sample size is relatively unimportant. However, the six healthy children (aged 4-5.5) participating do not adequately represent the target group of hospitalised children (aged 3-5). Therefore, the system should be tested with an expanded, diversified participant pool and hospitalised children before implementation.

On top of that, the current measurements only take a few minutes and the child or the robot takes constant actions. This does not represent the future situation properly, as hospitalised children have continuous access to technology. Consequently, significantly greater amounts of data are obtained over extended periods in such scenarios. Therefore, the test duration should be extended to provide a clear overview of the actual behaviour towards the technology over time. With these tests, the intra-individual variability can be explored for further exploration of the tool for wellbeing assessment. Additionally, the combination of the technology with the behavioural assessments executed by trained hospital staff should be investigated.

As mentioned in the research of N. Kousi [12], a history between the robot and the child is essential. During the tests, it was seen that some children needed time to understand the technology and get comfortable around it. Therefore, this should not be neglected in future research. By creating a history between the child and the robot, data for referencing the child's behaviour is obtained. Each child behaves differently, which means that when a child is not energetic, it is not, per definition, not feeling well. Therefore, analysing intra-individual changes can be of great value.

7.2 Improvement and enhancement

There are many teething issues since this is an exploration study in which a prototype is developed and evaluated. The detailed evaluation of the prototype is described in appendix K. Before implementation, these issues should be addressed, as data should be obtained more frequently. Additionally, there are many possibilities for improving and enhancing the technology, a few of which are addressed in this section.

7.2.1 General

First, the software could be easily adapted to different languages, making it a versatile tool. The technology is not bound to be used in hospital settings, meaning it is widely applicable. Its versatility and ease of adaptation make it suitable for other target groups, such as the lonely elderly. Its easy adaptability makes it perfect for implementing person or target group-specific functionalities. This could include notifications on taking medication or checking in on the person. Since self-reporting is a widely used method for pain assessment, this could be very valuable. The lights of MiRo can be used for emotional expression [25]. Therefore, the technology can benefit both verbal and non-verbal expression of emotions.

7.2.2 Measurements

From current data, the potential for indications of behaviour was obtained. However, data from current sensors could be utilised better; the plushie can be enhanced with other sensors or the robot's sensors can be added to evaluate a child's behaviour.

The data from the sensors of the plushie is currently not entirely used. The IMU has a 3-axis accelerometer and gyroscope, and only the magnitude of the gyroscope is used. Analysis should be done to show if using the other information might lead to more valuable insights into the child's behaviour. Also, the amount of pressure applied could indicate a child's feelings. Hard squeezing can be discriminated from hugging to use for further analysis.
Furthermore, the current model only shows if there is any interaction. For future implementation, the data should be used as input for a model using the intensity and frequency of interactions to provide insights into a child's behaviour. The model could be trained with testing data from a large test group to improve the accuracy of wellbeing assessment.

Complementary to the current sensors, the plushie could be enhanced with other sensors to improve the model. For example, a light sensor could be added to observe if the plushie is under the blankets or a moist sensor to measure suckling. Additionally, there are still many opportunities to measure physiological parameters. This leads to measuring more diversified behavioural and physiological parameters that could indicate pain. Eventually, this could lead to a more comprehensive and accurate assessment of a child's wellbeing.

Additionally, the sensors embedded within the robot, as described in section B, could be integrated into the system to complement current measurements. Its cameras can be combined with machine learning to identify if the child is in bed or not, as well as the facial expression, body position, or potential grabbing of a wound. Also, the robot can specify the direction of looking and conclude on the child's attention. The robot's microphone could be used in addition to the microphone of the plushie for data processing to pinpoint certain important sounds, such as the child's voice, for speech recognition.

Therefore, developing a machine learning-based model trained with data from many children, including inter- and intra-individual variability, can provide a baseline to compare (changes in) behaviour and thus provide insights into a child's wellbeing.

7.2.3 Wellbeing enhancement

The power of play is explored but leaves room for improvement. If the child enjoys playing with the technology, it could provide companionship, distraction and comfort. Therefore, enhancing its possibilities is of great importance. First, personalisation of the robot to suit the preferences of each individual could lead to an improved relationship [12]. This could enhance the engagement and thus improve their wellbeing. For this reason, it is essential to create various games, stories and educational activities with the technology to suit a child's interests.

In conclusion, while the current study lays the foundation for the technology, many opportunities remain for further development and refinement. By creating an algorithm including advanced sensor capabilities to measure the child's behavioural and physiological parameters, the system can assess a child's wellbeing while providing companionship and distractions for hospitalised children.

References

[1] Cambridge dictionary;. Available from: https://dictionary.cambridge.org/dictionary/english/well-being.

[2] Ferrari OI, Zhang F, Braam AA, van Gurp JAM, Broz F, Barakova EI. Design of Child-robot Interactions for Comfort and Distraction from Post-operative Pain and Distress. Association for Computing Machinery (ACM); 2023. p. 686-90.

[3] Drendel AL, Kelly BT, Ali S. Pain assessment for children: Overcoming challenges and optimizing care. Pediatric Emergency Care. 2011 8;27:773-81. Available from: https://journals.lww.com/pec-online/Fulltext/2011/08000/Pain_Assessment_for_Children__Overcoming.21.aspx.

[4] Rokach A. Psychological, emotional and physical experiences of hospitalized children. Clinical Case Reports and Reviews. 2016 01;2.

[5] Robots for pain management in children;. Available from: https://www.4tu.nl/nirict/Projects/All_projects/Robots%20for%20pain%20management%20in%20children/.

[6] The hospital environment linked pain evaluation robot;. Available from: https://www.ram.eemcs.utwente.nl/research/projects/helper.

[7] Kory-Westlund JM. Implications of children's social, emotional, and relational interactions with robots for human–robot empathy. Routledge; 2023.

[8] Miro-E;. Available from: https://www.miro-e.com/.

[9] Jeong S, Santos KD, Graca S, O'Connell B, Anderson L, Stenquist N, et al. Designing a socially assistive robot for pediatric care. Association for Computing Machinery, Inc; 2015. p. 387-90.

[10] Nunez E, Hirokawa M, Suzuki K. Design of a Huggable Social Robot with Affective Expressions Using Projected Images. Applied Sciences 2018, Vol 8, Page 2298. 2018 11;8:2298. Available from: https://www.mdpi.com/2076-3417/8/11/2298/htmhttps://www.mdpi.com/2076-3417/8/11/2298.

[11] Tumakaka GYS, Nurhaeni N, Wanda D. Squeezing a squishy object effectively controls pain in children during intravenous catheter insertion. Pediatric Reports. 2020;12.

[12] Kousi N. Play to Design; 2023.

[13] Kurtin NB. ADORA creating a better recovery;.

[14] Hossain MB, Kong Y, Posada-Quintero HF, Chon KH. Comparison of Electrodermal Activity from Multiple Body Locations Based on Standard EDA Indices' Quality and Robustness against Motion Artifact. Sensors. 2022 5;22.

[15] Korving H, Zhou D, Xiang H, Sterkenburg P, Markopoulos P, Barakova E. Development of an AI-Enabled System for Pain Monitoring Using Skin Conductance Sensoring in Socks. International Journal of Neural Systems. 2022 10;32.

[16] Kropf E, Syan SK, Minuzzi L, Frey BN. From anatomy to function: the role of the somatosensory cortex in emotional regulation. NLM (Medline); 2019.

[17] Blount RL, Bs KAL. Behavioural assessment of pediatric pain; 2009.

[18] Walco GA, Goldschneider KR. Pain in children: A practical guide for primary care. Humana Press; 2008.

[19] Jakub Zieliński TZ Monika Morawska-Kochman. Pain assessment and management in children in the postoperative period: A review of the most commonly used postoperative pain assessment tools, new diagnostic methods and the latest guidelines for postoperative pain therapy in children; 2020.

[20] Mathews L. Pain in children: Neglected, unaddressed and mismanaged. vol. 17; 2011. .

[21] Twycross A, Voepel-Lewis T, Vincent C, Franck LS, Baeyer CLV. A debate on the proposition that self-report is the gold standard in assessment of pediatric pain intensity. The Clinical journal of pain. 2015 7;31:707-12. Available from: https://pubmed.ncbi.nlm.nih.gov/25370143/.

[22] Argüello-Prada EJ, Valencia RDM. On the use of indexes derived from photoplethysmographic (PPG) signals for postoperative pain assessment: A narrative review. Biomedical Signal Processing and Control. 2023;80:1746-8094. Available from: https://doi.org/10.1016/j.bspc.2022.104335.

[23] Niu T, Liu M, Fang Y, Liu Y, Zhang X. Post-operative pain in children: Comparison of pain scores between parents and children. 2023. Available from: https://onlinelibrary.wiley.com/doi/10.1111/jpc.16420.

[24] V LoBue ea. Handbook of Emotional Development. Springer International Publishing; 2019.

[25] Collins EC, Prescott TJ, Mitchinson B, Collins EC. Saying It with Light: A Pilot Study of Affective Communication Using the MIRO Robot Ethical and Societal Impacts of Emerging Technologies View project The MiRo Project View project Saying it with light: A pilot study of affective communication using the MIRO robot; 2015. Available from: https://www.researchgate.net/publication/310442402.

[26] Prescott TJ, Mitchinson B, Conran S, Robotics S. MiRo: An Animal-like Companion Robot with a Biomimetic Brain-based Control System. 2017. Available from: http://dx.doi.org/10.1145/10.1145/3029798.3036660.

[27] UART vs I2C vs SPI – Communication Protocols and Uses - Latest Open Tech From Seeed; 2020. Available from: https://www.seeedstudio.com/blog/2019/09/25/uart-vs-i2c-vs-spi-communication-protocols-and-uses/.

[28] Gomez C, Oller J, Paradells J. Overview and evaluation of bluetooth low energy: An emerging low-power wireless technology. Sensors (Switzerland). 2012 9;12:11734-53.

[29] Nakamura Y, Arakawa Y, Kanehira T, Fujiwara M, Yasumoto K. SenStick: Comprehensive Sensing Platform with an Ultra Tiny All-In-One Sensor Board for IoT Research. Journal of Sensors. 2017 10;2017:1-16.

[30] What Is the Python Global Interpreter Lock (GIL)? – Real Python;. Available from: https://realpython.com/python-gil/.

[31] multiprocessing — Process-based parallelism — Python 3.12.1 documentation;. Available from: https://docs.python.org/3/library/multiprocessing.html.

[32] threading - Thread-based parallelism;. Available from: https://docs.python.org/3.8/library/threading.html#threading.Thread.

[33] asyncio - Asynchronous I/O;. Available from: https://docs.python.org/3.8/library/asyncio.html.

[34] Carroll JM. Five Reasons for Scenario-Based Design. Proceedings of the 32nd Hawaii International Conference on System Sciences; 1999. .

[35] Sugimine S, Saito S, Takazawa T. Normalized skin conductance level could differentiate physical pain stimuli from other sympathetic stimuli. Scientific Reports 2020 10:1. 2020 7;10:1-12. Available from: https://www.nature.com/articles/s41598-020-67936-0.

[36] Korving H, Sterkenburg PS, Barakova EI, Feijs LMG. Physiological Measures of Acute and Chronic Pain within Different Subject Groups: A Systematic Review. Pain Research and Management. 2020;2020.

[37] Getting Started with XIAO nRF52840 — Seeed Studio Wiki;. Available from: https://wiki.seeedstudio.com/XIAO_BLE/.

[38] CAP1203 datasheet. Available from: http://www.microchip.com.

[39] HX710(A/B) AVIA SEMICONDUCTOR 24-Bit ADC with Built-in Temperature Sensor (HX710A) 24-Bit ADC with (DVDD-AVDD) Voltage Difference Detection (HX710B);. Available from: www.aviaic.com.

[40] Atmospheric pressure - Wikipedia;. Available from: https://en.wikipedia.org/wiki/Atmospheric_pressure.

[41] Dertien E. projects:weafing [Electronic Thingies for Fun Stuff];. Available from: https://wiki.edwindertien.nl/doku.php?id=projects:weafing.

[42] Union E. B REGULATION (EU) 2017/745 OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 5 April 2017 on medical devices, amending Directive 2001/83/EC, Regulation (EC) No 178/2002 and Regulation (EC) No 1223/2009 and repealing Council Directives 90/385/EEC and 93/42/EEC (Text with EEA relevance); 2021.

[43] Union E. B DIRECTIVE 2009/48/EC OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 18 June 2009 on the safety of toys (Text with EEA relevance) (OJ L 170 30.6.2009, p. 1); 2009.

Part III
Appendix

A Assessment tools

The Children's Hospital of Eastern Ontario Pain Scale (CHEOPS) can be used for children from 1 to 7 years old. It is based on observation of the child's behaviour as stated in table A.3. The child requires a medical intervention if the score is above or equal to 8. Above or equal to 5 means the child should be considered to receive a medical intervention. The assessment should be done once every 3 hours or more after operations.

Table A.3: The Children's Hospital of Eastern Ontario Pain Scale (CHEOPS) [19].

Parameter	Criteria	Score	Definition
Cry	no cry	+1	Child is not crying.
	moaning	+2	Child is moaning or quietly vocalizing silent cry.
	crying	+2	Child is crying, but the cry is gentle or whimpering.
	scream	+3	Child is in a full-lunged cry; sobbing; may be scored with complaint or without complaint.
Facial	smiling	0	Score only if definite positive facial expression.
	composed	+1	Neutral facial expression.
	grimace	+2	Score only if definite negative facial expression.
Child verbal	positive	0	Child makes any positive statements or talks about other things without complaint.
	none	+1	Child not talking.
	other complaints	+1	Child complains, but not about pain, e.g., 'I want to see mommy' or 'I am thirsty'.
	pain complaints	+2	Child complains about pain
	both complaints	+2	Child complains about pain and about other things, e.g., 'It hurts' and 'I want my mommy'.
Torso	neutral	+1	Body (not limbs) is at rest; torso is inactive.
	shifting	+2	Body is in motion in a shifting or serpentine fashion.
	tense	+2	Body is arched or rigid.
	shivering	+2	Body is shuddering or shaking involuntarily.
	upright	+2	Child is in a vertical or upright position.
	restrained	+2	Body is restrained.
Touch	not touching	+1	Child is not touching or grabbing at wound.
	reach	+2	Child is reaching for but not touching wound.
	touch	+2	Child is gently touching wound or wound area.
	grab	+2	Child is gently touching wound or wound area.
	restrained	+2	Child is grabbing vigorously at wound area.
Legs	neutral	+1	Legs may be in any position but are relaxed; includes gentle swimming or separate-like movements.
	squirm/kicking	+2	Definitive uneasy or restless movements in the legs and/or striking out with foot or feet.
	drawn up/tensed	+2	Legs tensed and/or pulled up tightly to body and kept there.
	standing	+2	Standing, crouching or kneeling.
	restrained	+2	Child's legs are being held down.

Another frequently used assessment tool is The Face, Legs, Activity, Cry and Consolability (FLACC) tool. The tool is made for children from 2 months to 7 years old and for other children who are unable to state their pain level verbally, e.g. children who are asleep. It is also based on the child's behaviour, as seen in table A.4, but with slightly different criteria than CHEOPS. The score should be interpreted as following table A.5. If the score is above 3, medical interventions are needed.

Table A.4: The Face, Legs, Activity, Cry and Consolability (FLACC) tool [19].

Categories	Scoring		
	0	1	2
Face	no particular expression or smile	occasional grimace or frown, withdrawn, disinterested	frequent to constant frown, clenched jaw, quivering chin
Legs	normal position or relaxed	uneasy, restless, tense	kicking, or legs drawn up
Activity	lying quietly, normal position, moves easily	squirming, shifting back and forth, tense	arched, rigid or jerking
Cry	no cry (awake or asleep)	moans or whimpers, occasional complaint	crying steadily, screams or sobs, frequent complaints
Consolability	content, relaxed	reassured by occasional touching, hugging or being talked to, distractible	difficult to console or comfort

Table A.5: FLACC score intrepretation [19].

Score	**Interpretation**
0	Relaxed and comfortable
1-3	Mild discomfort
4-6	Moderate pain
7-10	Severe discomfort/pain

B MiRo

The robot chosen for the Hospital Environment Linked Pain Evaluation Robot (HELPER) research project is MiRo-e [2]. A summary of the robot's behaviour (1), mechanics, hardware (2), and software setup (3) is given to explore its possibilities.

1 Behaviour

MiRo-e is a commercially available mammal-like robot created for research and education [8]. The development of its brain is based on that of animals. Its affective behaviour corresponds to this innovative brain-like control. Subsequently, the robot's control is layered into three levels: the spinal cord, brain stem and forebrain, each running on a separate processor [26].

This comprehensive code allows MiRo to act like an animal, including emotional expression. MiRo displays emotion through its lights and movements as summarised in table B.1. It reacts to interactions and its environment due to data processing of the included sensors [25]. The spinal processor communicates with the brain stem processor via the Serial Peripheral Interface (SPI), which communicates via USB with the forebrain processor. Via the MiRoApp, the configuration and demo mode can be accessed and the robot can be controlled. The code for MiRo can be written from scratch, or (a variation to) the demo mode can be used.

Table B.1: Emotional expressions of MiRo [2].

Emotion	Posture and lights on body	Movement of robot	Interaction trigger by a human
Content	Eyelids nearly closed, darker shade of green lights. Slow movements around the space	Slowly drives around, bob head gently, slight rhythmic tail wagging, cooing sounds	Petting by a person makes it content/happy
Happy	Rainbow of colours moving around, similar to content but more energetic.	Drives around at a faster speed, chirping noises, tail wagging quickly.	Petting by a person makes it content/happy
Sad	Lowered head, eyes nearly closed. Blue colour. Ears turned outwards. Tail down.	Slow blinking, sad noises. Tries to spot a person by head movements	Not touched for a short time
Tired	Stops moving, eyelids almost closed	Eyelids closing slowly, head slow movement down.	Not touched for a long time
Sleeping	Eyes closed, no wheel movements	Rhythmic breathing behaviour, no or snoring sounds	Not touched when tired
Angry	Red lights, ears facing back, tail up stationary	Ears small twitchy movements	Walk away from person; angry when shaken
Surprised	Eyes wide open. The head raised. Ears facing front. Colour yellow.	Stand still in the described posture (deer in headlight)	Touched when sleeping

2 Mechanics and hardware

The robot weighs around three kilograms. The battery allows six active or 12 standby hours and recharging takes five hours. The code for MiRo runs on a Raspberry Pi 3B+ and the four microcontrollers, which allow Bluetooth and WiFi connections.

The technical specifications of MiRo-e are summarised in figure B.1. The wheels enable the robot to drive and rotate. The robot has kinematic movements, such as lifting, yawing, and pitching of the head, and cosmetic movements, such as moving the ears, eyes, and tail. The wheels and neck include feedback sensors. Additionally, the robot includes a speaker that can produce prerecorded audio fragments and 6 LEDs in the body that can be controlled separately.

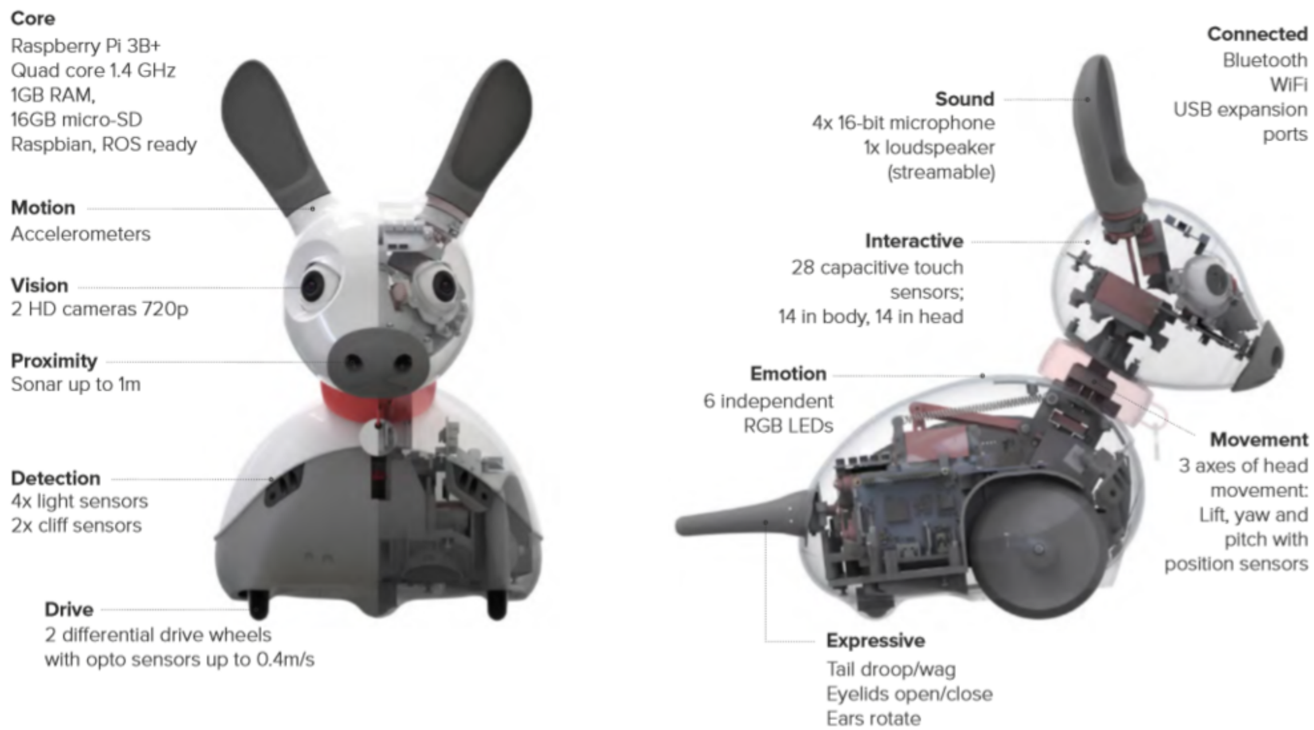


Figure B.1: Technical specifications of MiRo-e [8].

MiRo also has included sensors, enabling it to respond to its environment. The following are included:

1. Four light sensors at each side of the base.
2. Two, sonar, cliff sensors are pointed downwards from the front.
3. Capacity sensors along the body's inside and over the head's top and back.
4. Stereo microphones in the base of the ears, one inside the head and one inside the tail.
5. Camera's in the eyes.

3 Setting up MiRo developer environment

To learn to code, the developers of MiRo made platforms called **MiRoCODE** and **MiRoCLOUD**. In its easiest form, MiRo can be controlled using low-code programming tools. The level can be increased by creating simple Python code that drives the robot or the simulator.

The MiRo Development Kit (MDK) can be installed for more complex projects. It is possible to write the code for MiRo from scratch. However, the current code is pervasive and has many opportunities. Parts of the code are written in C/C++, and parts in Python.

The robot can be developed on-board or off-board. An Android device is helpful, and a wireless network is required. Furthermore, a powerful Linux computer with Secure Shell (SSH) is needed.

A few installation and configuration steps must be taken to write and test code on the robot. The versions and URLs used are stated below, and the steps are described. First, a functional laptop with Linux Ubuntu and a code editor such as Visual Studio Code and Python (v3) should be installed. On the Android device, download the MiRo-e application.

	version	**URL**
Ubuntu Linux	20.04.6 LTS 64-bit	https://releases.ubuntu.com/focal/
ROS	Noetic	http://wiki.ros.org/ROS/Installation
MDK	R210921	http://labs.consequentialrobotics.com/miro-e/software/
Pip	20.0.2	
Python	3.8.10 64-bit	
MiRoApp	version 2.2.0	Appstore

3.1 ROS

The robot uses three types of interfaces. SSH, Robot Operating System (ROS) and RobotInterface. ROS officially runs on Ubuntu, so Ubuntu Linux is the robot's preferred operating system (OS). ROS serves as an intermediary layer between the OS and the functional aspects of a robot. It establishes a framework to serve as a simplification between the layers through organisation. The ROS master keeps track of the Nodes within a system. Nodes can have a publisher or a subscriber role, as seen in figure B.2. Within ROS, communication is established through topics. The publisher node can write messages about a topic a subscriber can read.

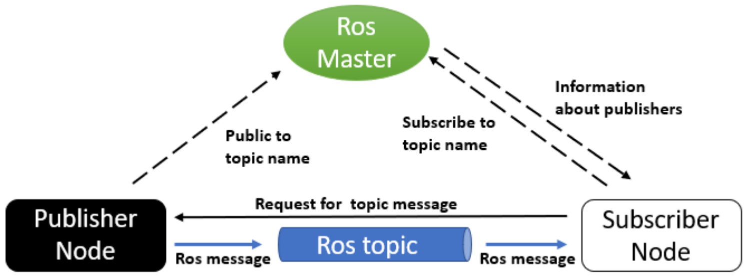


Figure B.2: ROS terminology

Thus, ROS (Noetic) should be installed first. With the ROS functionality rqt, the nodes/topics are visualised while using the needed functionalities. The result, figure B.3, shows streaming and control.

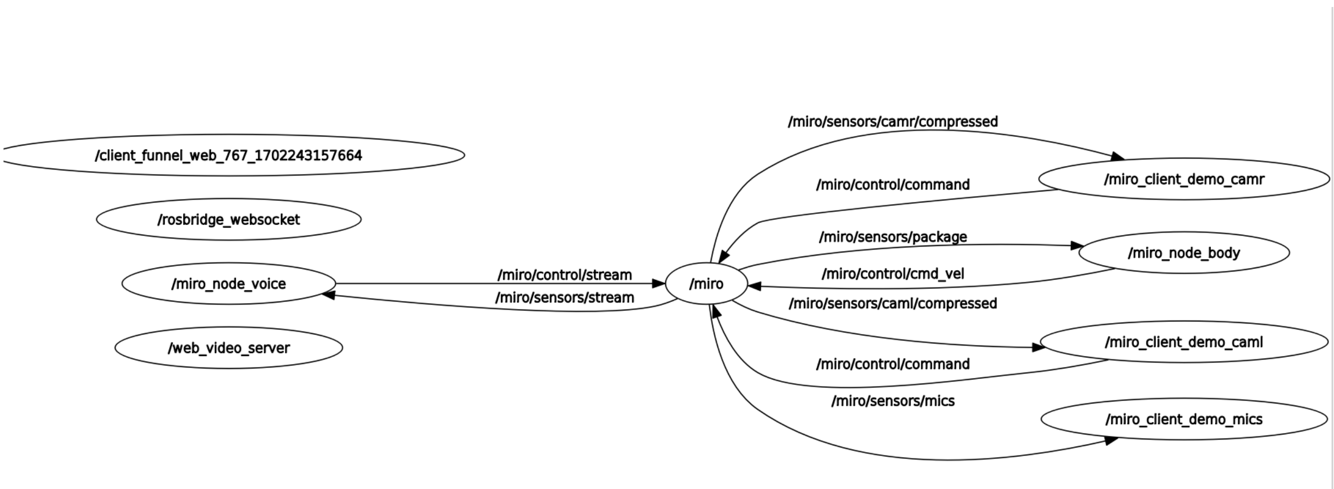


Figure B.3: The nodes and topics used for the streaming and control functionalities of MiRo, visualised via ROS rqt.

3.2 MDK

Then, the MDK should be installed. The installation steps can be found on: http://labs.consequentialrobotics.com/miro-e/docs/index.php?page=Developer_Install_Steps_Install_MDK.

3.3 Network

After installing the MDK, the robot must be configured on the same network Address. It does not need WiFi. For this, the robot presents an SSH interface. The steps for configuring the robot to the network can be found on: http://labs.consequentialrobotics.com/miro-e/docs/index.php?page=Developer_Install_Steps_Configure_MDK_Configure_Network.

Since challenges regarding these steps were faced, a summary of their solution is given:

1. Connect the robot with the Android device via the MiRo application.
2. Write down the IP address
3. Make sure the workstation is connected to the same IP address as the robot (thus, android device)
4. `nano ~/.bashrc`

   ```
   export MIRO_ROBOT_IP=x.x.x.x (your robot's IP address here!)
   source ~/mdk/setup.bash
   ```

5. Try opening a new terminal prompt. If it is not yet working, continue:
6. in the MiRo app, the settings can be switched from dynamically to statically. Then, in */mdk/setup.bash*, the IP address can be adjusted too.

After correct configuration, opening the terminal will result in a similar notification as stated in figure B.4.

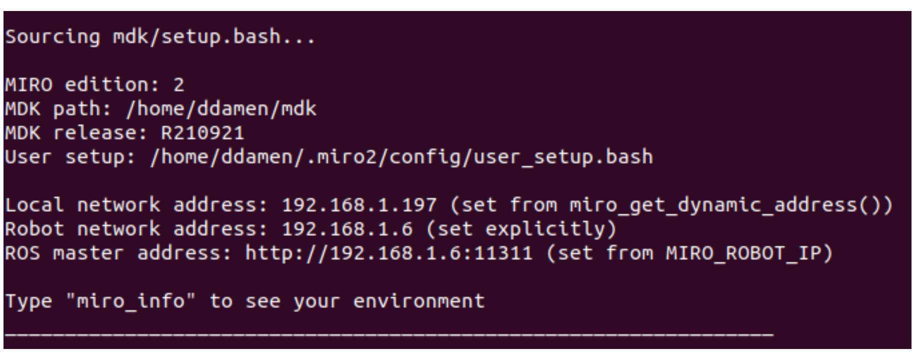


Figure B.4: The terminal will state a similar note after the correct configuration of the robot.

The MDK contains scripts to test the off-board development environment. These examples are implemented using the Python programming language and include code for tasks such as audio playback and controlling the robot kinematics. This is especially useful when support is desired from the company as it allows it to identify and tackle a problem efficiently. The testing code is located at:

```
/mdk/bin/shared
```

4 Movement control

To be able to control the robot, some know-how is required. Therefore, an explanation is provided. This is based on *client_test.py*.
The state of each joint contains information on the position [m or rad], velocity [m/s or rad/s] and effort/force [Nm or N] that is applied in the joint. Therefore, a class named **JointState** exists.

4.1 Kinematics

As stated in figure B.1, the neck of MiRo has three axes, which allow the head to lift, yaw and pitch. The movements and frames can be seen in figure B.5.

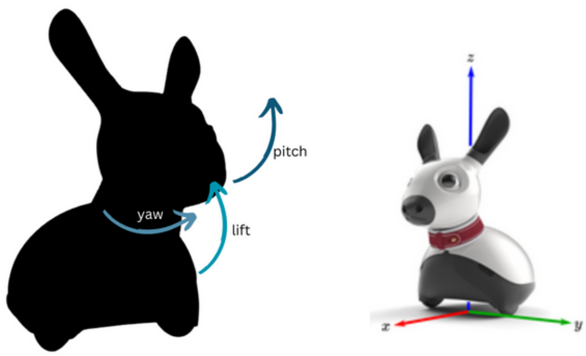


Figure B.5: Left, the 3-axis movements of MiRos head [self]. Right, the coordinate system of MiRo [8]

The kinematic frames in the robot form a chain. As can be noticed in figure B.5, lift and pitch rotate along the y-axis and yaw along the z-axis. The position sensors provide feedback to the system to calculate the actions required. This could entail separate or combined movements.

First, a time-dependent variable, x, is calculated as shown in equation B.1. Take that t is updated after each $0.02s$, then the maximum, $x = 1$, is reached after 100 iterations and the minimum, $x = -1$, after 300 iterations.

$$x(t) = sin(\frac{\pi}{4}t) \tag{B.1}$$

$$x(0) = 0 \tag{B.2}$$

$$x(2) = 1 \tag{B.3}$$

$$x(6) = -1 \tag{B.4}$$

Then, the desired position, as a function of time, of the lift, yaw and pitch, can be calculated using equations B.5, B.6 and B.7. Each position is given in radians. The positions are calculated in their own kinematic frame.

$$lift[rad] = \frac{\pi}{9}x + 0.5 \tag{B.5}$$

$$yaw[rad] = \frac{\pi}{4}x \tag{B.6}$$

$$pitch[rad] = \frac{\pi}{12}x + rad(-7) \tag{B.7}$$

It can be noted that the motions are restricted to specific ranges. This is to respect the physical limitations of the robot. The **lift** of the head is restricted from 90° (completely down) to 10° (up). However, the robot is physically able to achieve greater and smaller angles for other purposes, such as locking the head. The 'standard' position of the neck is at 30°.

The **yaw** movements are physically restricted from 90° to −90°. However, it is now restricted to only half of this range. At maximum x, the head turns to its left with 45° and at minimum to its right with −45°.

The **pitch** movement range is $-22°$ to $8°$. At maximum, its nose points downwards and, at minimum, upwards. A detail of this movement is that it cannot hold its head upward.

4.2 Cosmetic

The cosmetic joints require x as stated in equation B.8.

$$x(t) = sin(2\pi t) \tag{B.8}$$

$$xc2(t) = sin(\pi t) \tag{B.9}$$

$$x(0) = xc2(0) = 0 \tag{B.10}$$

$$x(0.25) = 1 \tag{B.11}$$

$$x(0.5) = -1 \tag{B.12}$$

$$xc2(0.5) = 1 \tag{B.13}$$

$$xc2(1) = -1 \tag{B.14}$$

For all cosmetic joints, x is used as input to calculate *cos_data*.

$$cos\_data[i] = \frac{\pi}{6}x + \frac{\pi}{6} \tag{B.15}$$

Thus, the resulting value is within boundaries [0-1]. The $cos\_data[i]$ list contains six elements.

Table B.2: The cosmetic movements based on the value resulting from equation B.15.

i	cosmetic	if $cos\_data = 0$	if $cos\_data = 1$
0	tail	up	down
1	tail	left	right
2	left eye	open	closed
3	right eye	open	closed
4	left ear	to front	to side
5	right ear	to front	to side

4.3 Wheels

A velocity must be determined based on the elapsed time to drive the wheels. This gives variable "v" that ranges between 0 and 1. The linear movement can be determined as stated in equation B.16.

$$twist.linear.x = v * wheels \tag{B.16}$$

For the robot's spinning, in addition to variable v, variable **spin** is needed for calculation B.17.

$$twist.angular.z = v * 6.2831 * spin \tag{B.17}$$

4.4 Lights

The 6 LEDs in the body can be set with RGB. Therefore, the list msg_illum_data contains six elements corresponding to these LEDs. The first three are for the right side of the body, and the last three are for the left side. A general form of assigning the colour is as follows:

```
msg_illum.data[i] = (q << (2-i)*8) | 0xFF000000
```

In which q is a value between 0 and 255, which allows adjustments of the colour. The value is not shifted (i=2) for the red colour, shifted by 8 (i=1) for green or 16 (i=0) positions for blue.

C Software and Hardware foundation

Some background knowledge is required for the hardware choices of the plushie and the software development for both the plushie and MiRo. Therefore, a short and general description of the principles used is provided in this chapter.

1 Communication protocols

A microcontroller (MC) is the brain of an embedded system. Sensors will be attached from which data should be read, processed and transmitted. The data signal can be transferred through wires by a communication protocol that suits the purpose at its best. MCs often offer a variety of communication protocols tailored to specific situations. Often, these are serial protocols to minimise the required number of pins and complexity. For reading sensor data, three different protocols stand out [27]:

- **Universal Asynchronous Receiver/Transmitter (UART):**
  UART is the most simple but also slowest of the three. It only allows one master and one slave. It uses the transmit (TX) and receive (RX) pins to send and receive digital signals.
  It is relatively easy and can be used for, for example, MC to portable computer (PC) data transmission.
- **Serial Peripheral Interface (SPI):**
  SPI is four wired, Master Out Slave in (MOSI), Master In Slave Out (MISO), serial clock (SCK) and a data pin-out (CS).
  SPI is often used for displays and sensors. The MC exchanges data with a sensor in (MISO) and out (MOSI) using the SCK and CS.
- **Inter-Integrated Circuit (I2C):**
  I2C allows multiple slaves and masters, is relatively easy and is two-wired. It uses the (shared) Serial Data line (SDA) and a Serial Clock (SCL) of the MC. I2C can be used when multiple devices need to communicate through the same bus.

The created embedded system should be able to not only transfer data within the system itself but also communicate with other devices; different methods could be considered. A MC could transfer data via a wired connection or wireless communication methods. There is a variety of conventional methods, each serving its specialisation. For example, Via Wireless Fidelity (Wi-Fi) can send large amounts of data over a wide range. However, it is complex and consumes a lot of energy. Also, it can be hard to implement network authorisation access securely. Conversely, Bluetooth only works on a short range and allows lower data transfer rates than Wi-Fi. The encryption might be easier, making it easier to create secure data transfers. However, Bluetooth could suffer from interference in settings such as hospitals.

Furthermore, Bluetooth Low Energy (BLE) can be considered. BLE works differently from traditional Bluetooth. The benefit of BLE is its reduced power consumption ($< 15mA$) and cost [28]. This makes it very suitable for wearables. BLE works via Gaussian frequency shift modulations, reaching up to $2Mbit/s$. The framework that enables BLE to transfer data is the Generic Attribute Profile (GATT) [29]. The profile is displayed in figure C.1.

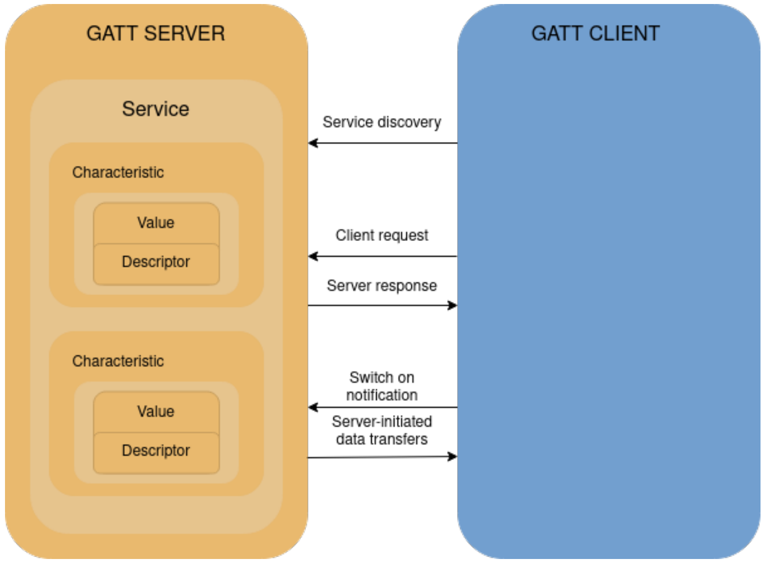


Figure C.1: GATT server and client and its core components.

In BLE, the device holding data is the server and the other is the client. The Generic Access Profile (GAP) is a specification of BLE that holds the advertisement information. The GATT server advertises its existence to potential clients. When a client discovers the server, it can connect. The GATT server is also known as the peripheral. It holds the definitions of services and characteristics. The GATT client, or central, requests data from the Peripheral. The characteristics can have a *Read*, *Write* or *Notify* property of a combination. This allows the client to perform the corresponding actions.

2 (A)synchronous programming

The code is running synchronously by default. However, complex systems might require functions to run in parallel.

In Python, a variable corresponds to a memory location [30]. Python keeps track of the number of references to a variable, and when this drops to 0, the memory for the variable is released. This could induce racing conditions when multiple variables are accessed in multiple threads. That is why Python has the Global Interpreter Lock (GIL). With GIL, only one thread at a time can be executed since it requires the interpreter lock for code execution. Thus, GIL limits the simultaneous running of multiple threads.

While this process simplifies memory management, it introduces challenges. Therefore, different libraries and methods can be considered to achieve the desired parallelism in code execution. Although some of the principles are general, this chapter is specifically designated for Python.

2.1 (Non-)blocking functions

Blocking functions require finishing the execution of the operation before continuing to run the code. This could be the case when data is requested but not directly available. On the other hand, non-blocking functions allow the code to continue running while waiting for the outcome or output of the non-blocking function.

2.2 Multiprocessing

Parallelism is the execution of multiple operations at the same time. This could be beneficial since it could increase the execution speed of code significantly. However, in Python, multiple threads can not run simultaneously. To bypass the limits of GIL, subprocesses can be used instead of threads [31]. A process is an instance of the Python interpreter, which makes the GIL not an issue. This allows the spread of tasks over the Central Processing Unit (CPU).

2.3 Threading

A thread describes a part of a process [32]. The distribution of tasks over multiple threads is called threading. With threading, concurrency takes place. With concurrency, the execution of threads may overlap each other. Thus, concurrency makes use of parallelism but is more than just that. Each process contains at least one thread. When the main thread is executing, with threading, a new thread can be started to run in the background. Since threading does not require completing the Input/Output (IO), efficiency increases. Therefore, threading is ideal for Input/Output bound tasks.

In asynchronous programming, event loops are frequently used. Event loops allow scheduling of execution and stopping of (parts of the) code. In threading, events can be used as follows.

```
def task(event):
    while not event.is_set():
        print("Function is running!")
        time.sleep(1)


if __name__=="__main__":
    task_event = threading.Event()

    task_thread = threading.Thread(target=task, args=(task_event,))

    task_thread.start()

    time.sleep(5)

    # stop the function by setting event
    task_event.set()

    # wait till the thread is finished
    task_thread.join()
```

In this example, an event named task_event is created. Then, a new thread, named task_thread is started with this event. The function runs until the event is set, which is done after 5 seconds.
It can be seen that this principle functions similarly as a “While True” loop.

2.4 Async(io)

Another method to improve efficiency by decreasing the running time is using asynchronous programming [33]. In contrast to multiprocessing and threading, Asynchronous Input/Output (Async) functions do not run in parallel and only use one CPU core and thread. However, achieving concurrency across multiple cores is possible.

Async functions, also co-routines, use cooperative multitasking. This means that when a co-routine is awaiting an operation, such as reading data, it can pause the co-routine while continuing the event loop. Thus, the function requires an awaitable. This can be another co-routine or an object. The function continues when the awaitable (represented by x) is obtained. When awaiting another co-routine, co-routine chains can be created.

```
async def function():
    # pauses here until x is received
    x = await Read_data()
    return x
```

Thus, Async functions are particularly useful for processes with long waiting periods. Async functions allow manipulations of event loops, allowing specifications as *’run_until_complete’* or *’run_forever’* to be assigned to the loop.

D Design plushie

The plushie is designed as an addition to MiRo to assess and improve a child's wellbeing. It must be a complementary item for interactions and play. Therefore, the plushie must be integrated into the pre-operative history of the child with MiRo, as seen in research [12]. Thus, its design requires some thought. Its possible appearance should fit into the possible storylines of the child with MiRo and the plushie. This is especially important since it could increase the child's potential to interact with the technology, contributing to fulfilling its goal.

Complementary to the plushie's role in wellbeing assessment, it should be equipped with sensors contributing to this goal.

Therefore, first the design method is provided (section 1), followed by its elaboration, the possible appearances of the plushie (section 2), the sensors with potential for this purpose (section 3) and lastly the design conclusions (section 4). Afterwards, the steps of the development are described in more detail.

1 Design method

The plushie is designed to assess and improve the wellbeing of the child. It allows the introduction of new possibilities for interaction with the robot. In this section, the steps of the design process are described in more detail.

Besides the performance of the plushie, the appearance also requires some thought. The plushie must be appealing to augment the child's interaction with the technology. For this reason, user-centered design (UCD) is chosen as the design method for the plushie. Using this approach, the user's needs and desires are the focus. To enhance the child's wellbeing, they are the centre of attention instead of maximising the capabilities of the technology. This is also why UCD is chosen over interaction-based design (IBD). The type of UCD used is scenario-based design (SBD). In SBD, the typical activity of the child with the technology is envisioned in scenarios. SBD gives certain advantages [34] as it is helpful for the action and reflection of the plushie and the child's needs regarding the technology are respected. Therefore, this approach suits the needs of the design and development.

Initially, scenarios will be outlined on which the possible appearances and sensors will be based. From this, design conclusions will be drawn and a prototype will be developed and evaluated after testing.

Since this research focuses on a child after surgery, the situation is often very similar. The general problem is sketched as follows:

The child needs to go to the hospital since it needs medical attention. In the hospital, they hear that they need to undergo surgery. They are brought into a hospital bed and introduced to MiRo and the plushie, as described by N. Kousi [12]. After a short play session, they are provided with anaesthetics. Then, the child is brought into the operating room. After surgery, the child will wake up in the recovery room, finding the plushie on its bed and MiRo on its bedside table. This leads to various situations, described by providing the scenarios that will help the design's understanding, musts and desires. The scenarios are not based on conditions that occurred but are based on imagination.

1.1 Scenario 1

Meet Max, a 4-year-old boy who just underwent surgery. Before surgery, he received MiRo and a plushie from the hospital. MiRo is a robot mammal that interacts actively with Max through his movements, sounds and lights. Hidden in MiRo are a variety of sensors which observe Max' behaviour before the operation as well as afterwards to be able to compare them. In contradiction to MiRo, the plushie is soft and huggable. This does not take away that the plushie also contains sensors to be able to measure when Max is holding the plushie and how it is moving without notification of Max. Before the surgery, Max got the time to get comfortable with the plushie and MiRo. They went on an adventure together since MiRo needed some help. Max was a hero for helping MiRo! This led to a connection between them.
Max wakes up in the recovery room after his operation. He still feels a little bit sleepy and feels pain. He immediately grasps the plushie. This interaction is measured and transmitted to MiRo. As a response, MiRo asks if Max is okay. Max starts crying really loud because he does not understand where he is and what this pain is that he is feeling. MiRo tells him that the operation was successful and that his parents will come in a few minutes. Max listens carefully but is still sobbing while he is hugging the plushie. MiRo asks if he can help Max, since Max helped him a few hours ago. Max is not consolable. Therefore, MiRo informs the nurse that Max might need painkillers. When the painkillers finally work, Max is calm. He touches MiRo with curiosity and they even play a game together. Max enjoys the companionship and distraction while also being monitored by the technology.

1.2 Scenario 2

Meet Max, a 4-year-old boy who just underwent surgery. Before surgery, he received MiRo and a plushie from the hospital. MiRo is a robot mammal that interacts actively with Max through his movements, sounds and lights. Hidden in MiRo are a variety of sensors which observe Max' behaviour before and after surgery to be able to compare them. The plushie contains a variety of sensors as well. He is mostly soft but also has conducting materials on the outside to be able to measure even more parameters. Before surgery, Max and the technology went on an adventure together. Max helped MiRo to get better from the light storm by using the plushie! Max was a hero and measurements were done un-noticeably.
When Max wakes up in the recovery room after his operation, he feels a bit sleepy. He finds MiRo sitting on the table next to his bed and the plushie next to him in bed. He grasps the plushie and looks around. He is curious what is going on. MiRo receives data from the plushie and notices that Max is awake. He does not like hugging the plushie that much. He asks if he is okay. Max babbles and pets MiRo. MiRo senses this and reacts positively on this interaction. He asks if he can help Max with something yet? Max babbles again and says ”Where is mommy?” MiRo says that she will be here soon and asks if he wants to play a game. If so, he can grasps the plushie. Max says Yes! He feels okay and interacts positively with the technologies and enjoys the distraction until his parents can be around him again.

1.3 Scenario 3

Meet Max, a 4-year-old boy. He is in the hospital and a little nervous because of this new place with all new people. When the nurse tries to ask him things, he gets a little shy and does not respond. His parents try to talk to him but he is not consolable. The nurse gives him MiRo, a robot mammal, and a plushie for companionship. When the nurse walks out of the room, Max explores the possibilities of MiRo carefully. He pets him and MiRo responds positively with a sort of purring and by showing lights. When Max gets a little more confidence, he also starts to explore the plushie. The plushie is soft and when he squeezes it, MiRo responds because there are sensors hidden in the plushie that are transmitted to MiRo. Then, they start exploring an imaginary world together with puzzles included. During this adventure, the plushie and MiRo together measure the behaviour and interaction of the child as well as some physiological parameter discreetly. This forms a valuable baseline of the state of Max.
As Max wakes up after his surgery, he feels disoriented and sleepy. However, he quickly notices MiRo next to him on a table and the plushie in his bed. He reaches for the plushie and holds it close. Their companionship comfort Max directly.
MiRo receives the sensed movement of the plushie which indicate that Max is awake. MiRo then asks if Max is okay to which Max does directly respond. MiRo asks if Max is hurt? Max looks at MiRo and starts to pet it. MiRo responds with affection on this positive interaction.
When Max stops petting MiRo, MiRo tells Max that the nurse will come later and asks if he wants to play a game to pass the time. Max responds with excitement.
Max is focused on MiRo and the plushie during the game while the technology is observing and measuring Max. The amount of interaction is large which indicates that Max feels okay. However, his body temperature is very high which is reported to the nurse.

When the nurse asks how Max is feeling, Max does not say anything. The nurse does not see anything odd but knows about Max' fever. Thus, even though Max is behaving normally, he still needs extra medication to partly tackle his fever.

1.4 Scenario 4

Meet Max, a 4-year-old boy. He is in the hospital and a little nervous because of this new place with all new people. When the nurse tries to ask him things, he gets a little shy and does not respond. His parents try to talk to him but he is not consolable. The nurse gives him MiRo, a robot mammal, and a plushie for companionship. When the nurse walks out of the room, Max explores the possibilities of MiRo carefully. He pets him and MiRo responds positively with a sort of purring and by showing lights. When Max gets a little more confidence, he also starts to explore the plushie. The plushie is soft and when he squeezes it, MiRo responds because there are sensors hidden in the plushie that are transmitted to MiRo. Then, they start exploring an imaginary world together with puzzles included. During this adventure, the plushie and MiRo together measure the behaviour and interaction of the child as well as some physiological parameter discreetly. This forms a valuable baseline of the state of Max.
After the operation, Max wakes up with MiRo on his bedside and the plushie next to him in bed. Max still feels a little sleepy and thus he grasps the plushie and takes an extra nap. MiRo observes Max' closed eyes and low heart beat and therefore does not actively interact with Max yet. Max suckle on the plushie while he is sleeping. The plushie senses a sudden temperature change and redirects this to MiRo. MiRo alarms the nurse of this change. The nurse wakes Max and checks in on him. From the sudden temperature change, she knew that Max had pain and choose to give him a fever suppressing medicine.

1.5 Scenario 5

Meet Max, a 4-year-old boy. He is in the hospital and a little nervous because of this new place with all new people. When the nurse tries to ask him things, he gets a little shy and does not respond. His parents try to talk to him but he is not consolable. The nurse gives him MiRo, a robot mammal, and a plushie for companionship. When the nurse walks out of the room, Max explores the possibilities of MiRo carefully. He pets him and MiRo responds positively with a sort of purring and by showing lights. When Max gets a little more confidence, he also starts to explore the plushie. The plushie is soft and when he squeezes it, MiRo responds because there are sensors hidden in the plushie that are transmitted to MiRo. Then, they start exploring an imaginary world together with puzzles included. During this adventure, the plushie and MiRo together measure the behaviour and interaction of the child as well as some physiological parameter discreetly. This forms a valuable baseline of the state of Max.
Max wakes up after the operation. He has pain and grasps his tummy. He starts to cry softly. MiRo, which is placed next to Max' bed, obtains information from the plushie which is next to Max in bed. With this information and the sensor data of MiRo, MiRo creates a clear overview of the situation. Since Max is crying, MiRo starts talking: "Hey, you are awake. Are you in pain?". Max does not respond and makes clamps even harder to his tummy. MiRo asks if Max can grab the plushie to squeeze in. After a moment confusion, Max does what is asked. He hugs the plushie and the pressure sensor senses this. MiRo starts distracting Max while giving a signal to the nurse that Max is hurt.

1.6 Scenario 6

Max is a 4-year-old boy. He went to the hospital because his tummy hurt. After a consultation with the doctor, it was concluded that he needed immediate surgery. Max does not understand what is happening and he sobs softly. He is brought to another room and may lay down in a bed. The hospital staff around him is very busy and does not have time to console Max. His mother is stressing and asking a lot of questions to the nurse. Max feels very lonely and scared alone in this large hospital bed. Then, a nurse brings him MiRo and a plushie. Max likes the plushie and immediately holds it tight. He is looking surprised and curiously at MiRo.
MiRo is a robot mammal which includes a speaker, lights and actuators to move its head, tail and drive around. Max touches MiRo gently which activates the robot. MiRo starts to wag its tail and make satisfied sounds. Max' attention focuses on the technology instead of its environment. What Max does not know is that discreetly, the plushie and MiRo have sensors included that observe the behaviour, interaction and physiological parameters of Max. Together they will make a baseline of how Max is feeling before and after surgery. Max further plays with its robotic toys and discovers an imaginary world.
After surgery, Max wakes up and finds MiRo on his bed-stand and the plushie next to him in bed. He immediately feels more comfortable in this weird and a little scary environment. He also sees his mom next to him who is asking many questions. He does not want to respond, he wants his mom to be calm. Luckily, he can cuddle with his toy. From the data that is obtained, it was noted that Max feels okay. His mom can see this conclusion on her mobile app which makes her feel more okay too.

1.7 Scenario 7

Max, a 4-year-old boy, is admitted to the hospital for a surgical procedure. He is feeling anxious and scared in the unfamiliar environment. The nurse introduces Max to MiRo, a friendly robot mammal, and a plushie to help him feel more at ease. Max immediately takes a liking to the plushie and holds it close to him. MiRo, with its interactive features, actively engages Max in playful movements and sounds, providing a fun distraction.
Discreetly, both MiRo and the plushie are equipped with sensors to monitor Max's wellbeing and physiological parameters. The data collected will serve as a baseline to assess his wellbeing before and after the procedure.
As Max is taken into the operating room, he clings to the plushie for comfort. MiRo stays with him until he falls asleep, and the sensors observe his heartbeat and body temperature. The surgical team proceeds with the operation, while MiRo remains nearby, ready to engage Max as soon as he wakes up.
After the surgery, Max awakens in the recovery room feeling groggy and disoriented. He feels scared because of the weird sensations in his body. He moves wildly, tangling and pulling loose the wires that were attached to him. MiRo senses these movement and responds with gentle sounds and movements to ease his transition from sleep. Max reaches for the plushie, and the sensors detect his touch, indicating his need for comfort. At the same time, the hospital staff is alarmed of his state.
The nurse observes the measurements of Max' interactions with MiRo and the plushie, noting that his movements and heart rate have returned to a stable state after a while. She consoles him even more by telling him that the operation went successful and giving him ice cream. The collected data helps the medical team assess Max's recovery progress and ensure he is receiving the appropriate post-operative care.

2 Appearance

As mentioned, the looks of the plushie should be appealing to stimulate interaction. Understanding child psychology and making it an age-appropriate, comforting plushie is complex and time-consuming research as it is. The currently considered appearances are designed to fit in a story with MiRo, as seen in previous research [12]. Each child has their personal preferences, making an individual design not applicable. However, that is not the scope of this research and thus, a thorough investigation of the looks of MiRo and the plushie will be left for future research. For this reason, only a brief balancing of possible looks will be discussed.

2.1 Carrot animal

The plushie is a carrot which can be zipped open with a child-friendly zipper. Underneath that layer is a hidden bunny. This allows the child to discover the bunny, making it more interesting. Additionally, this combination gives more possibilities to fit the plushie into the adventures that the child, the robot and the plushie will go through together. If the child does not feel that the carrot is appealing, it has the bunny and vice versa. This takes the preferences of children's individuality a little more into account. It is easy to fit sensors in this concept as well.

2.2 Animal pillow

The plushie is a pillow that looks like an animal. The child can sleep and lie on it, making it a helpful place to put sensors close to the child. A drawback is that the child might not play like it as with other conceptual plushies. The animal look makes it easy to fit into the storyline with MiRo since they can all go on adventures together.

2.3 Cloud

The plushie cries while on an adventure with the child and MiRo. The cloud feels lonely and will feel better if the child hugs it and gives it company. After surgery, the cloud could return the favour if the child feels lonely or sad. The cloud has a soft top, which could include sensors and its legs contain conducting material to measure physiological data. This increases the amount and variety of measurements but decreases the huggability of the plushie.

2.4 Magic wand

The magic wand can be used to help MiRo with its adventures. The form of the magic wand might decrease how appealing it is to hug. On the contrary, the concept might increase the interaction the child has with it since a magic wand is a utensil. This might encourage the child to swing, move and hold the magic wand. It could include only discrete sensors but could also include conducting materials where the child holds it.

3 Sensors

To measure (indicators of) pain, various sensors can be used. The parameters indicative of pain are either physiological or behavioural. A physiological parameter that changes due to pain is skin conductance [35]. Therefore, measuring the electrodermal activity (EDA) can be an option to integrate into the system. This method measures the skin's resistance with, for example, a finger cuff or wristband.

Another method which can be used to indicate pain is photoplethysmography (PPG) [22]. With this method, infrared light is emitted through the blood, for example, the finger. The amount of light the finger absorbs is used to calculate various cardiovascular parameters indicative of pain.
Other physiological parameters are explored for measuring pain but show low technology readiness levels [36].

CHEOPS and FLACC, appendix A, are frequently used behavioural assessment tools. Since these are validated tools, their significance should be respected. The parameters of these tools are considered for automation via sensors' measurements to capture a child's behaviour. The parameters included in CHEOPS are cry, facial expression, child verbal, torso movement and positioning, touching wound and leg movement and positioning. In FLACC, the facial expression, leg movement and positioning, activity, cry and consolability are scored.

Initially, the consolability of the child can be investigated by using a speaker and a microphone. Including a microphone also allows capturing crying, child verbal and partly child activity.
Then, torso movement and positioning, touch wound, and leg movement and positioning can be captured with on-body position, acceleration sensors, or a camera with processing.
Therefore, the plushie has the potential of measuring the parameters used in the assessment tools.

Lastly, the child's interactions with the technology could be part of the activity parameter used in the assessment tools and can indicate the child's feelings solely. Therefore, the sensors in the plushie must be able to measure the child's interactions with the plushie. The sensors must be chosen such that a representation of the child's behaviour can be obtained as well as possible. From section 1, it was seen that the child could hold, shake, throw, move, squeeze, hug, stump or be just gentle to the plushie. Therefore, the plushie must be able to capture these interactions at a minimum.

First, the Inertial Measurement Unit (IMU) can measure acceleration and angular rotation. Therefore, it can capture movement, shaking and throwing. It is a small and convenient sensor. However, this does not measure squeezing and hugging. Thus, the pressure applied to the sensor could also be measured to fulfil this need. This would still not be able to capture the whole spectrum of interactions the child has with the robot. To further increase the representation of the actual situation, capacity sensors also need to be included. With this, holding the plushie can be captured even while the child executes no active movements.

Additionally, a microphone would be beneficial. A microphone can capture a child's talking, babbling or crying, which could be further analysed.

4 Design conclusions

4.1 Appearance

Since the appearance is not of focus for this research, the choice of it for the prototype is not optimally well-considered. The magic wand is chosen for the prototype of the plushie, given its intuitive nature for movements. Therefore, holding the plushie will come naturally for the child, optimising their interactions. It brings lots of opportunities for storylines and is, therefore, perfectly suitable for the prototype.

4.2 Sensors

One of the main requirements of the sensors is that they do not restrict a child's movements. Therefore, it is chosen not to work with wired sensors. As mentioned in previous research [12] [13], EDA and PPG could be integrated into headbands or wristbands, which could be part of a superhero story with MiRo. However, it is now chosen to focus exclusively on developing a plushie. Therefore, and because of the exclusion of wired sensors, these sensors are left out of the scope of this research.

Therefore, a combination of an IMU, microphone, capacitive pads and pressure sensors is the minimum number of sensors that would capture the parameters from the assessment tools and various interactions of a child with the plushie. This allows the child to play without restriction, allowing and capturing their natural behaviour with the technology.

For simplification, the activity of each sensor is captured in only one variable. The IMU's primary function is to measure the intensity of translation and rotation in the plushie; the direction is considered irrelevant. Thus, the magnitude of the angular velocity is chosen since this can best represent the smaller movements of the plushie as well. For the microphone, the peak frequency is selected as the representative since the frequency of the sound can be linked to the emotion in a child's voice.

4.3 Communication plushie-robot

Based on the requirement to develop a wireless plushie, the wireless communication methods are considered as stated in appendix C. Bluetooth Low Energy (BLE)'s low energy consumption characteristic makes it very suitable for making wearables or, in this case, a plushie. However, choosing BLE as the wireless communication method comes with a challenge.

Currently, MiRo-e can be controlled using an application on a smartphone. Thus, MiRo-e is the Peripheral to the smartphone since it listens to its commands.
When a plushie joins the technology, the plushie serves the robot. This would mean that the robot should take on the central role. However, a BLE Peripheral can only be connected to one BLE central. The workaround is that the robot switches roles. However, this means that when sensor data is requested, the robot stops responding to its commands from the smartphone.

Thus, an alternative approach, which is suitable for the experimental setting of the research, is used. The plushie remains the GATT server and a BLE connection is established with a laptop, as seen in figure D.1. As an advantage of this method, the sensor data can be tracked in real-time and stored on the device. Then, a connection between the laptop and the robot is established via a network. As a benefit, the robot can also be controlled through the computer in real time. Thus, with the alternative approach, the situation can be monitored closely and interventions are possible when desired. As a drawback, a laptop is needed for this setup.

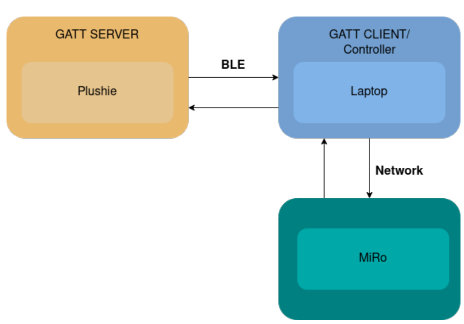


Figure D.1: The alternative approach for providing a BLE connection

E Development Plushie

1 Hardware

After obtaining the insights of the design analysis, the hardware choices will be elaborated. The considerations will be explained to align with the objectives of the project. Since this is a non-funded project, there are limitations to these choices. First, the individual components are described, followed by the section, 1.7, dedicated to the electric circuit.

1.1 Microcontroller

While a MC is not a conventional computer, it holds many functionalities required for an embedded system. When a MC satisfies the system's needs, it is preferred over a computer because of power efficiency, costs and size. The embedded system developed for this study only requires a microcontroller since it is needed for simple data collection, processing and transmission.
The MC should be able to read sensor data from a microphone, IMU, pressure sensor and capacity sensors and communicate this data to another device via BLE. It would be advantageous if these sensors were already integrated into the MC. Otherwise, certain communication protocols are needed. For a foundation of the communication protocols, read Appendix C1.
The MC should be able to function without wires, thus with a battery energy supply. There needs to be a possibility to charge the battery, but this does not necessarily have to be with the MC.
The MC needs to be suitable for wearables; thus, it needs to be small but powerful. Therefore, the needs and requirements stated in table E.1, should be considered for choosing a MC.

Table E.1: The requirements and needs of the MC.

should have	**nice to have**
USB	small size
allow battery energy supply	an integrated microphone
allow BLE	an integrated IMU
powerful	an integrated Capacity sensor
SPI interface	an integrated pressure sensor
UART interface	
I2C interface	

With these requirements, the Arduino Nano 33 IoT was considered. This MC satisfies the should-haves and has an integrated IMU. At the moment of writing, it costs 22,80 euros. As another option, the Xiao Seeed NRF528400 Sense was considered. It also satisfies the musts and includes a microphone and an IMU. Above that, it is smaller than the Arduino Nano. Therefore, this was chosen as the MC for the plushie. The MC is displayed in figure E.2.

(a) (b)

Figure E.2: An overview of the Xiao Seeed NRF52840 Sense microcontroller front (a) and back (b).

This MC, now the MC, allows programming in MicroPython, CircuitPython and Arduino. It contains a Bluetooth antenna to establish BLE. Its power consumption is very little, with its standby power consumption of $< 5\mu A$. Therefore, the MC suits the purpose of the plushie. The MC supports Arduino IDE, which is the utilised programming language.

1.2 Microphone

The MC has a built-in microphone based on pulse density modulation (PDM) [37]. The frequency of sampling can be adjusted.

1.3 IMU

The embedded IMU within the MC comprises a 6-axis system, including the acceleration and angular velocity across the three spatial directions alongside a temperature sensor. This could allow expansion for future versions. The IMU uses the I2C communication protocol.

1.4 Capacity

The capacity sensor should measure if the magic wand is touched. Therefore, a simple and available sensor suffices. This is the CAP1203, as seen in figure E.3 [38]. It uses I2C communication, which means it connects to SDA and SCL. Its sensitivity can be adjusted.

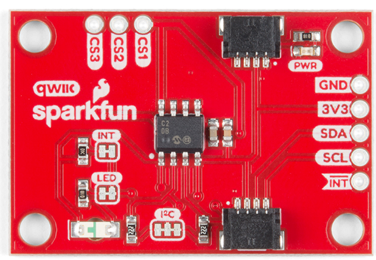


Figure E.3: The CAP1203 sensor, used as a capacity sensor for the prototype.

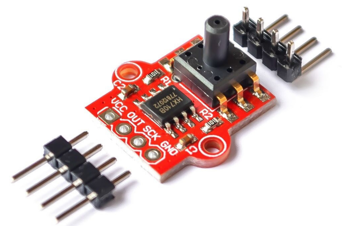


Figure E.4: The HX710B, used as the air pressure sensor for the prototype.

1.5 Pressure sensor HX710B

The pressure sensor was selected without consideration of its specifications, as it was obtained based on availability and practical constraints. Additionally, it was important to maximise the possibilities of the plushie with minimal quality and quantity of sensors.

The air pressure module "HX710B" is used [39]. Its communication protocol is the Serial Peripheral Interface (SPI), which is four-wired. Therefore, the sensor uses the serial clock (SCK) and an output pin, D0, to obtain data. It operates between 1.8-5.5 volts. In this case, it is connected to the 3.3-volt power supply and the ground. It uses the amplified difference between the inverting and non-inverting input and an analog-to-digital converter (ADC).

The pressure sensor measures the force on the area in the range $0 - 40kPa$. Since the earth's atmospheric pressure is $101.325kPa$ [40], the relative air pressure should be measured and calibration steps are needed.

1.6 Battery

The battery is a Cellevia LP60 1730 3.7V 2.59 mAh lithium polymer battery, which is used because of availability.

Figure E.5: The Cellevia battery used for the prototype.

1.7 Circuit

A bit of foundation for the communication protocols is provided in chapter C.
The circuit is a variation from the described circuit (figure E.6): `https://wiki.edwindertien.nl/doku.php?id=projects:weafing`.

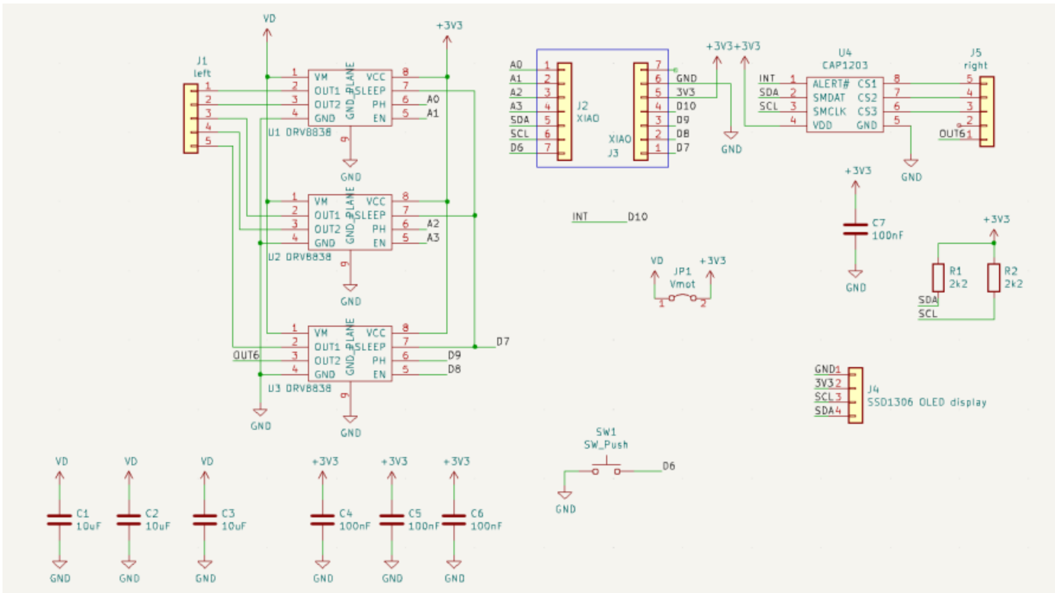


Figure E.6: Weafing control scheme [41]

The three capacitive touch sensor inputs are connected via SDA and SCL, as seen in figure E.6. The battery and pressure sensor are also connected to the microcontroller, as seen in figure E.7.

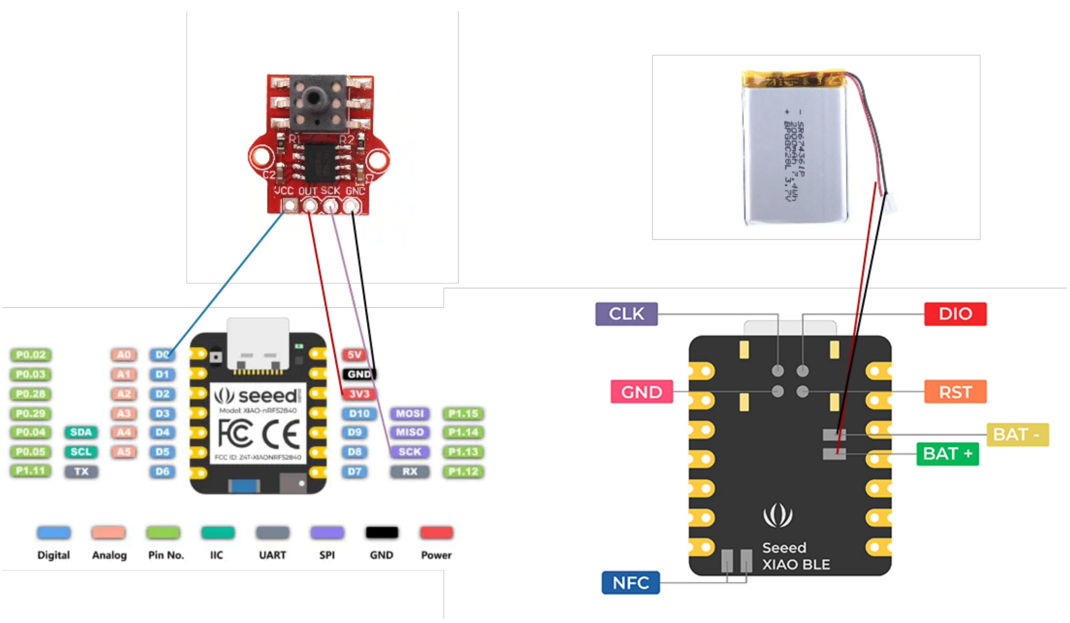


Figure E.7: Additionally to the circuit of the weafing schematic E.6, the air pressure sensor and battery are connected to the microcontroller as shown. The pressure sensor uses SPI.

1.8 Safety regulations

In the European Union (EU), the regulations of medical devices are documented [42]. The law for toys, corresponding to the age of the target group, is captured by the EU as well [43]. The technology used for HELPER needs to obey these laws. Thus, several requirements demand special attention for the plushie's design process. The first concern is to eliminate any choking hazards. This means that the plushie may not contain any loose small parts or that these are well attached. The material of the outside plushie is also a point of attention since it should be easy to clean for use on another child. As an alternative, the fabric can be used for one-time use. In that way, the child could take home the plushie, and a clean environment could be guaranteed. The child might suckle on the plushie, which may not cause dangerous situations regarding the electronics inside.
Data privacy in medical settings is a critical aspect. Therefore, sensitive data must be handled and stored with care.

The electronics may never cause an electric shock, so the electrical circuit must be well-designed and tested thoroughly. This also includes the battery in the plushie; battery safety demands special attention.
Eventually, before integrating the technology in hospitals, a medical certification must be obtained.

2 Tinkering a plushie

The choice of the appearance of the plushie is a magic wand. From the scenarios (section 1), it can be noticed that the plushie needs to be cuddly and appealing to hold and interact with while minimally disturbing the sensors inside.

Since this project has no funds, the materials and tools available are minimal. For this reason, tinkering is used to develop a prototype that suits the needs with the materials available. This way, creativity is stimulated and a solution within the possibilities is developed.

First, a squeezable needs to be developed. This system uses an air pressure sensor (as described in 1.5). The idea is to couple a balloon-like structure to the sensor. Then, the capacity pads can be placed on the balloon's surface, and the microcontroller and battery can be placed inside the star of the magic wand.
A clay mould was first created to create a specific-shaped balloon. Casting silicone was poured into this mould and allowed to dry. This process was then repeated for the other side, with a small tube inserted for air supply and a tool used to create a space inside the balloon. However, due to hardware limitations, the structure proved not optimally suitable in combination with the current air pressure sensor. The pressure on the silicone before expansion was already too high, making differences created by squeezing unnoticed. One solution could be using a different air pressure sensor, but another balloon was chosen instead due to tool limitations. It was also decided to stick with air as the balloon's content for safety reasons regarding possible plushie ruptures. A material that expands under less pressure had to be found so that differences could be observed. Therefore, regular latex balloons were considered. After calibration, the use of these balloons works within the desired margins. The balloons were filled with cotton to make squeezing them a comfortable experience.

The pressure sensor is attached, secured to the balloon, and protected with a first layer of fabric. On this layer of fabric, the copper foil of the two capacity pads is placed separately on the upper and lower parts.

Then, the sleeve for this balloon is sewed using simple fabric in a playful print. A star is attached to the ending, leaving space for the microcontroller. This coupling can be opened using Velcro.

Figure E.8: A photograph of the hardware circuit (left), then with the balloon and the magic wand cover (middle), and with the microcontroller and battery in the star and thus finished (right).

Then, an unsuccessful attempt to secure the microcontroller with silicon was made. The silicon blocked the BLE antenna. Therefore, isolation tape was used to protect the battery and microcontroller where needed.

3 Plushie software

The code for the plushie is developed in the Arduino integrated development environment (IDE) version 2.2.1 Linux 64-bit. The code of the plushie can be downloaded via https://github.com/daniquedamen/Plushie and uploaded onto the MC. Various libraries can be installed via the links in table E.2 or directly in the Arduino application.

Table E.2: Required installations with corresponding version and URL of the plushie.

	version	**URL**
Arduino IDE	2.2.1 Linux 64bit	https://www.arduino.cc/en/software
Arduino FFT	1.6.1	https://github.com/kosme/arduinoFFT
Sparkfun CAP1203	1.0	https://github.com/sparkfun/SparkFun_CAP1203_Arduino_Library
LSM6DS3	2015	https://github.com/arduino-libraries/Arduino_LSM6DS3
Xiao Seeed Microphone	2021	https://github.com/Seeed-Studio/Seeed_Arduino_Mic
HX711B	0.3.9	https://www.arduino.cc/reference/en/libraries/hx711/
Arduino BLE	1.3.6	https://www.arduino.cc/reference/en/libraries/arduinoble/

The class diagram of the code of the plushie is displayed in figure E.9. For clarification, the classes are described in more detail in the following subsections.
In Arduino, a sketch contains a '.ino' file. This file contains a setup function, which will run only once, and a loop function, which will loop. In the main file of the sketch, the BLE Class is initialised and the BLE loop will run once per 500 ms. This slight delay is achieved through keeping track of the loop time. This method is preferred over the conventional delay because, in this way, the code will remain responsive and read sensor data instead of waiting for a fixed delay. Since the code is not entirely serial structured, this is especially helpful.

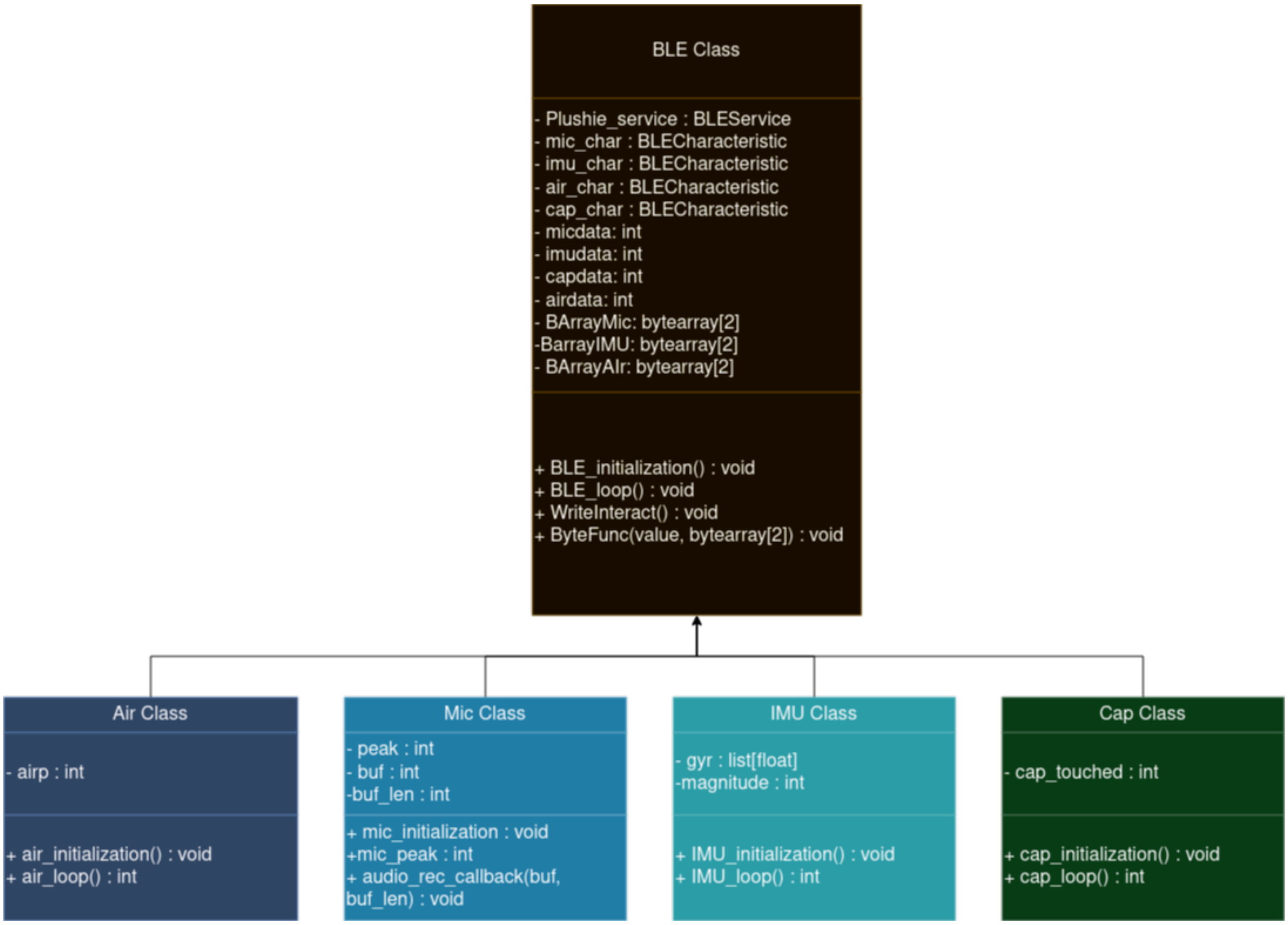


Figure E.9: A Class diagram in Unified Modeling Language of the code running on the microcontroller. The attributes of each class and the relationship between the classes are provided. Each sensor has its class and provides the BLE Class with the required information to write to the characteristics.

3.1 BLE peripheral

The "Arduino BLE" library is used for the BLE connection. Figure E.10 displays the BLE profile. Each sensor has its parameters and, therefore, its characteristics. The library defines the data types of a service and its characteristics. The data type of the plushie service is *BLEService*, which allows the assignment of a universally unique identifier (UUID). For the capacity, *BLEIntCharacteristic* is utilised since this will only hold integers. For the microphone, IMU and pressure, *BLECharacteristic* is chosen since this enables specifying the value size in bytes. The data from these sensors is too big to hold in one byte since one byte only allows for values smaller than 255.

In the constructor of the BLE Class, a 16-bit UUID is assigned to the service and each characteristic. Each characteristic gets only the read property assigned since the BLE client may not adjust the data on the characteristics but can read it when desired. The allowed value size of the microphone, IMU and pressure is 2 bytes, which will be enough for this data. This is observed from measurements.

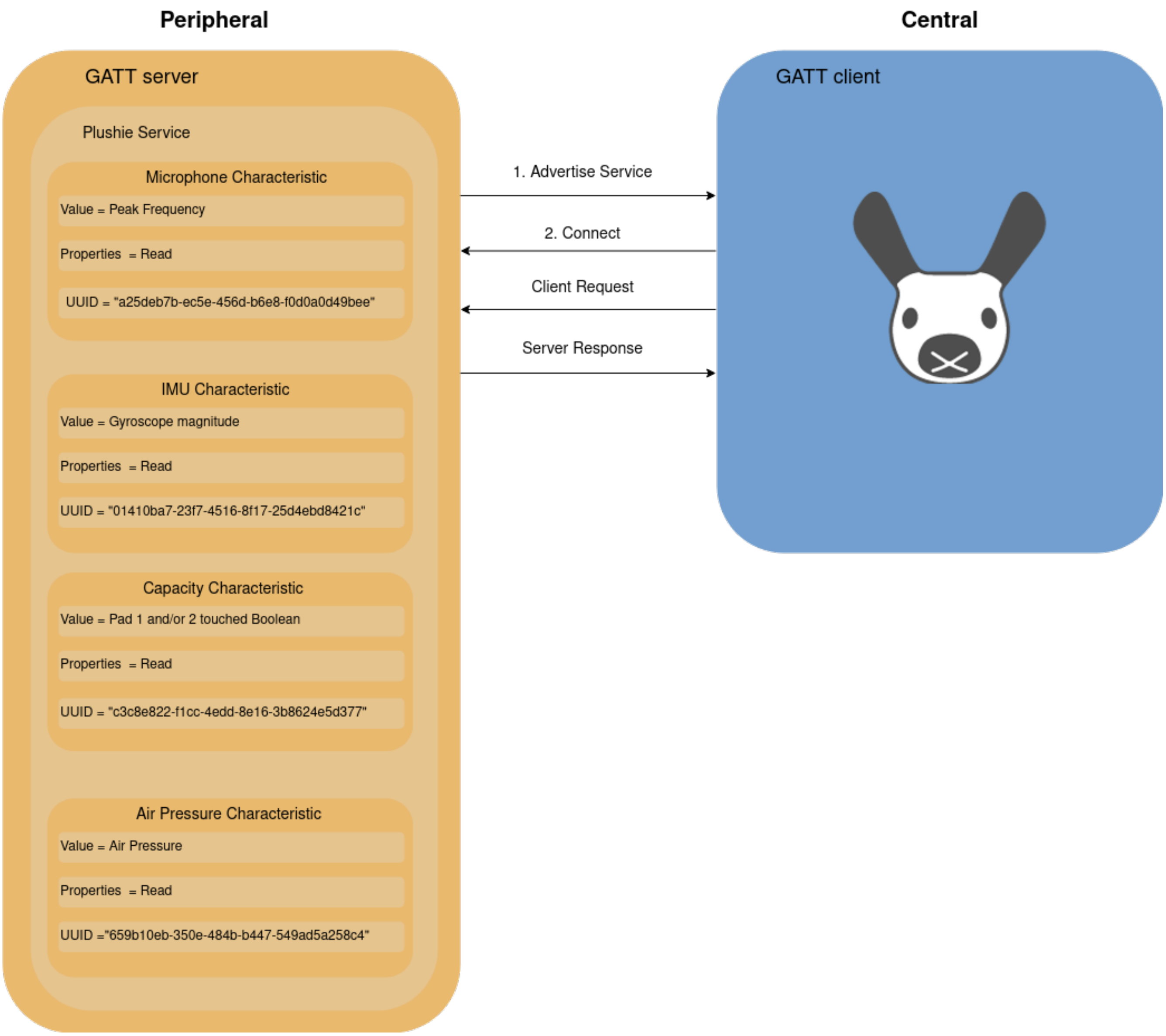


Figure E.10: The BLE GATT framework of the plushie and MiRo.

In the **BLE initialisation**, the service is assigned as the advertised service and the characteristics are coupled to the service. The sensors are initialised in this class as well.

In the **BLE loop**, advertisement is started. If a device is found, this device is the BLE central. If a device is found, the device will connect. When connected, the plushie remains advertising so that re-connection is possible in case of disconnections. When connected, *WriteInteract* is invoked.

In **WriteInteract**, the data is read from the functions in the classes of the sensors. The microphone, IMU and pressure sensor data are first transformed from integers to a 2-byte array with the *ByteFunc* function. Then, each parameter is assigned to the designated characteristic.

3.2 Microphone

The "Seeed Arduino Microphone" library is used for sound recording and processing. The "Arduino FFT" library is also used to calculate the signal frequency.

During **initialisation** of the microphone, the *audio rec callback* function is assigned as the callback function. This function will be invoked each time a new audio sample is available. This function converts the 12-bit Analog to Digital (ADC) value read by the microphone to a 16-bit Pulse Code Modulation (PCM) stored in recording_ buf[i]. This makes the signal suitable for further analysis.

In the function **mic peak**, this value is assigned as the real part for the fast Fourier transform (FFT), while the imaginary part is set to 0 to simplify the magnitude calculation. This is allowed since it is a real-valued signal. Then, a Hamming window is applied. This is a common filtering technique for finite duration signals and discrete Fourier transformations (FFT is a discrete form). It helps to reduce leakage and artefacts by modulation of the amplitude, which creates smoothing at the edges of the signal. Then, the forward Fourier transform is computed. As a result, information about the frequency is obtained. More specifically, the dominant peak frequency of the signal is received.

3.3 IMU

For the built-in IMU, the "LSM6DS3" library is used. With this library, data from the 3-axis accelerometer, the 3-axis gyroscope and the thermometer can be read. The library is initialised with an inter-integrated circuit (I2C) for data transmission.

The **initialisation** begins measurements of the IMU.

During the **IMU loop**, the three directions of the gyroscope are read as floats and then used to calculate the magnitude with subtraction of an offset of 2, which is the result of a small error in the IMU, as stated in equation I.1.

$$mag = \sqrt{x^2 + y^2 + z^2} - 2 \tag{I.1}$$

With the magnitude, the intensity of the rate of rotation can analysed for the combined axis.

3.4 Capacity

Using the "SparkFun CAP1203"' library, the process of **initialising** the capacity involves establishing a connection with the I2C bus for data transmission.

Within the **loop**, the status of the two capacity pads can be determined by checking whether they are touched. For convenience of data transmission, the values are combined to obtain one integer. If the lowest pad is touched (the middle one on the sensor), the parameter *cap touched* will become 1. If the upper pad is touched (corresponding to the right one on the sensor), ten will be added to *cap touched*. That way, *cap touched* can be 0, 1, 10 or 11.

3.5 Pressure

To measure the air pressure, the library "HX711B"' interface the HX711B semiconductor ADC.

The **initialisation** of the air pressure class includes setting the declaration of the data pin, A0, and the serial clock (SCK). For calibration, the value is scaled through *'scale'* and the offset is determined with *'tare'*. This is important since the surrounding air pressure could differ according to various parameters.

In **loop**, the airp parameter is obtained by taking the integer of the average of 5 measurements. If pressure is applied, the pressure that is measured is positive. A negative pressure would mean that a pulling force is discovered. Theoretically, this is impossible, but it can be noticed since the balloon deflates after squeezing. However, since this is not a measure of importance and will complicate data transmission, negative pressures are set to 0.

F Tests

The tests are designed to obtain valuable insights into the interactions and understanding of the target group regarding the plushie and the robot. This means these phases can not be implemented as the complete functionalities of the technology.

The tests are conducted with Dutch participants. Therefore, the robot's audio is in Dutch. However, for the readability of this section, the statements are translated into English. These phases are the first interactions of the child with the technology. It is divided into three parts, each with its approach to interacting with the plushie. With this division, the variance of the needs and desires of children is respected. Each action of the robot consists of a movement and audio. The complete overview of the actions can be read in appendix G 2; only the most relevant movements are stated. Each audio fragment is numbered with the phase and fragment numbers as (phasenumber_fragmentnumber).

1 Phase 1

In the first phase, the child can discover the magic wand independently. This starts with the robot saying:

"Hi! Nice to have you here. Grab the magic wand and discover my possibilities!" (ph1_1)

Then MiRo reacts positively on engagement with the magic wand, as stated in table F.1, but will not tell the child what to do. In this way, the child discovers the interaction possibilities and MiRo responds to them.

Table F.1: The reactions of MiRo to the interactions with the plushie

	Movement	**Audio**
shake	workout	"Cool! You used magic by shaking the magic wand." (ph1_3)
hold	wag	"Yes! If you hold the magic wand, you can talk with me." (ph1_4)
talk	ears	"Good job! I hear you." (ph1_5)
squeeze	spin	"You can squeeze as hard as you like." (ph1_6)

These actions are triggered when the corresponding sensor measures interaction when this was not the case previously. The order of the possible interactions is essential since the child holds the plushie when it shakes or squeezes it, but this does not have to be the same the other way around. Therefore, with this order, the possible correlations of the sensors are respected. When the child rediscovers a potential interaction, MiRo says:

"Great! What more can you do?" (ph1_2)

When the child has discovered every sensor, MiRo says:

"You discovered the magic wand! Now we continue to something fun!" (ph1_7)

It can occur that it is impossible to finish all the interactions for technical reasons or when the child experiences difficulty exploring the interactions. Then, (non-)verbal instructions can be given by the researchers, or the researchers can choose to continue to the next phase.

2 Phase 2

When the child has discovered the possibilities of interaction with the magic wand, the next phase is to play a game. The game menu gives the child the choice between the three games by interacting with the magic wand. The researcher also has the option to set a pre-chosen game. These games provide a distraction and entertainment method for the child. Additionally, these situations help create a connection between the child and the robot, contributing to the research's purpose. The phase starts with MiRo saying:

" If you want to play a game, squeeze in the magic wand." (ph2_8)

Then, after interaction with the child or the researcher:

“If you want to play dance party, shake the magic wand. If you want to play, guess the animal, squeeze. Otherwise, we will play Simon Says.” (ph2_9)

Again, a choice can be made if the child or researcher provides input. Otherwise, game three will be started.

2.1 Game 1

Game 1 is a dance party. In this game, the child plays against MiRo. Music will be played randomly, and when the music stops, the child and MiRo must stop dancing. The robot stops after a set time of 3 seconds. They win if the child is faster and no shaking is measured after the game stops. Therefore, the game goes as follows:

“Nice. I will play some music and then we dance together. When the music stops, we stop dancing. Who stops fastest wins.” (ph2_10)

Music plays: 2 possible audio fragments, one will be randomly picked. (ph2_11) or (ph2_12)

Then, there are two possibilities:

- “Congratulations, you won! Shake with the magic wand to continue.” (ph2_13)
- “Too bad! Try it again next time. If you want to continue, shake with the magic wand.” (ph2_14)

2.2 Game 2

Game 2 is guess the animal. In this game, the child gets the order to shake the magic wand if it hears a specific animal. Then, the child hears animal sounds in a random order. With the animals, MiRo moves. When the animal of the order is played, the sensor reads if the child won the game.

“Great! We now play Guess the Animal. I name an animal and when you hear that animal, you shake the magic wand.” (ph2_15)

Then, the possible commands are

- “Shake if you hear a donkey.” (ph2_16)
- “Shake if you hear a dog.” (ph2_17)
- “Shake if you hear a cat.” (ph2_18)
- “Shake if you hear a cow.” (ph2_19)
- “Shake if you hear a lion.” (ph2_20)

With the possible commands, the corresponding animal sounds will play in random order until the animal related to the command is played.

- *Cat sound* (ph2_21)
- *Cow sound* (ph2_22)
- *Dog sound* (ph2_23)
- *Donkey sound* (ph2_24)
- *Lion sound* (ph2_25)

When the child wins, (ph2_13) and otherwise (ph2_14) is played.

2.3 Game 3

Game 3 is Simon Says or Commando's, as the Dutch know it. Usually, you should carry out the commands when the word "Commando" or "Simon Says" is mentioned first. However, since the target group of this game is 3-5 years old, this might be too difficult. Therefore, There are just commands that the child needs to perform. When 3/5 commands are correctly executed, they win.

"Now we play Simon Says, to win, you need to do what I say." (ph2_26)

Then, five commands will be given in a random order. The possible commands are:

- "Say aaaa" (ph2_27)
- "Say Blablablablablabla" (ph2_28)
- "Do not do anything, but gently hold the magic wand" (ph2_29)
- "Shake the magic wand" (ph2_30)
- "Squeeze the magic wand" (ph2_31)

Then, the interactions with the magic wand will be checked and when it is correct, MiRo says:

"Good job, onto the next. (ph2_33)"

Otherwise (ph2_14) is played.

After five commands, it will determine if the child won, and (ph2_13) is played, or if it did not, (ph2_14) is played.

3 Phase 3

In the third phase, an interactive story is played. With this story about the history of MiRo, the connection between the child and MiRo can be amplified. Interactions are needed between the steps to continue. The story provides an accessible interaction method that suits more expectant and shy children.

"Do you want to hear a story? Then do a spell with the magic wand!" (ph3_34)

"Back in the days, in Techtopia, I lived as a free robot. But I could not speak. Therefore, I did not have many friends and did not feel truly happy. I often felt lonely. If you also feel this sometimes, squeeze in the magic wand." (ph3_35)

"On an afternoon, I met a boy named Daan. I did not understand him. He spoke a different language than I did. But despite that, Daan stayed with me. We played together outside on an afternoon in Techtopia. An old lady came to us and gave Daan a stick. It turned out to be a magic wand, the one you are holding! Shake it! " (ph3_36)

"Because of the magic wand, I can understand you! Just as I suddenly understood Daan. Daan and I did not understand how this was possible. But we were thrilled. We played happily together and I understood what Daan felt because he played with the magic wand. Therefore, I react to the magic wand. Try interacting with it!" (ph3_37)

"Very good! Now you probably think: How did you get here, MiRo? I will tell you the story! One day, Daan hurt himself. He had to go to the hospital. Just like you at this moment. I joined him. In the hospital, I played with many new friends in the hallway. If you want to be my friend too, say YES! " (ph3_38)

"As Daan once helped me, I will help others too. Daan saw that other children needed me, too. That is why we said our goodbyes and I live in the hospital now. I see many different things now and people are sweet to me. If you want to hear my story, please shake the magic wand." (ph3_39)

"I appreciate that. Thank you for helping me." (ph3_40)

4 Parental briefing letter

Looking for (dutch speaking) Robot Testers (aged 3-5): contribute to the research of a companionship robot for hospitalized children

Researcher: Danique Damen (Biomedical Engineering student, University of Twente), d.damen-1@student.utwente.nl, +31681961372

Supervisor: dr. ir. E.C. (Edwin) Dertien (Assistant professor, University of Twente, Robotics and Mechatronics), e.dertien@utwente.nl, +31534892778

Hi,
My name is Danique and I am currently working on my master thesis regarding the HELPER project. With this project, we are looking to see if and how a companionship robot ("MiRO") can be used for hospitalized children. We want to distract the child from feeling pain or discomfort next to unconsciously measuring the wellbeing of the child. We know that hospitalization can have a great impact on a child and hope that this research can contribute to alleviation of the negativity of the experience. The technology could also help the hospital staff by providing continuous data of the behavior of the child which makes it easier to assess the state of the wellbeing of the child and providing medication when necessary.

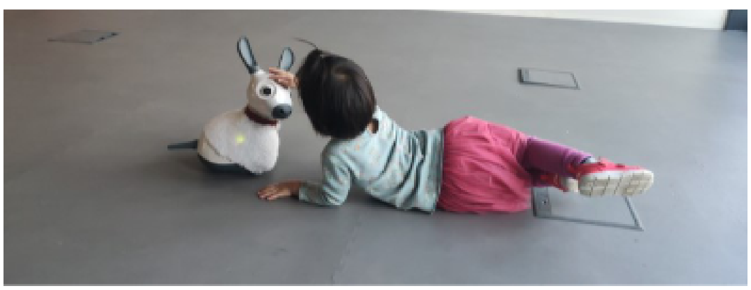


Figure 1: Participant in research with robot "MiRo"

Since we can not directly test the robot in the hospital, we first want to test our ideas of interaction between child and robot with healthy children. This includes playing games, storytelling with an accessoire of the robot, a Plushie. We want to test this in a regular setting, as at daycare de Vlinder.

Therefore, we would like to invite your child to contribute to this research project, as an expert and robot tester. With this letter, we would like to explain the aim of the project, what you (and your child) can expect and how we are handling the outcomes of the tests. We hope that everything is clear to you. If there are any questions left, you can reach us by phone or email.

Even if you do not want your child to participate in the research, or your child does not want to, your child is still free to explore playing with the robot. No data will be gathered from this if there is no consent.

About the research
The aim of the project is to see if we can gather useful information about the wellbeing of the child with a soft cuddly toy (a Plushie) to which the robot responds. The Plushie contains sensors to detect movement, squeezing, touch and sound. This information is sent to the robot for response. The reactions of the robot could stimulate interaction. These interactions allow for data collection.

The experiment is a session to play with the robot. During this session, your child will get to know MiRo, play a game and take part in an interactive story. As researchers, we will observe your child and help if needed. Also, an employee of de Vlinder will be present. We will not leave your child alone with the technology. The approximated duration of the session is 12 minutes. If there is lack of interest, the attention span of your child or something else does not allow it to continue, we will quit the experiment.

As researchers, we will do anything in our power to create a safe and relaxed atmosphere. If you suspect that your child could feel awkward or shy but is wellwilling for participation, please let us know. In that case we will take some extra time for the introduction of the technology.

We are not using any privacy related information as your name or address. We will only documentate the age and gender of your child as well as the behavior of your child relating to the technology.

During the session, we will documentate the observations. These observations simply hold any emotional expressions or comments during the session.
The data is anonymous and will possibly be used for other researchers and research publications.

Approving participation to session: Robot testing with storytelling and play

Select the boxes that apply to you:

	yes	no
I have read and understood the information	☐	☐
I agree that my child will voluntarily participate to the session and understand that my child may refuse to answer and quit at any time	☐	☐
I understand that my child will participate in a story and games in which the cuddly toy with sensors and robot will be used	☐	☐
I have understood that data will be saved and kept for research purposes and possibly for a scientific publication	☐	☐
I have understood that observations will be documented	☐	☐
I have understood that the data will be anonymous	☐	☐
(optional) I agree that comments of my child may anonymously be used for a scientific publication of this project	☐	☐
(optional) I agree that the results may be saved and kept for future research	☐	☐
(optional) I agree that comments of my child may anonymously be used for future scientific projects and publications	☐	☐

We are planning on making pictures during the experiments in which we will make your child unrecognizable. This is very valuable for my thesis. If you object, please let us know in the comment area.
If you only agree after seeing the blurred photos, please leave your email address too.

Signing

____________________ name (parent or guardian) | __________________ place, date | ________________________ signature

(Optional) Email-address:
Only necessary if you want to be updated on the research.

I declare that I tried to make the information as clear as possible to the participant to the best of my abilities and emphasized that participation is completely voluntary.

name researcher | place, date | signature

Contact details for further questions or remarks:

Danique Damen

d.damen-1@student.utwente.nl
+31681961372

Comments:

G Development MiRo software

1 Installation guide

To install the code required for the interactions of MiRo with the plushie, the plushie should be fully developed as described in Appendix D, and the developer environment should be set up for the off-board profile as described in the Appendix section B.3.

To provide both controlling the robot via the demo mode that the company develops as the new code, the code that is written is only an addition to the MDK. Therefore, it is of great importance that the code will not disturb the other code and, thus, is positioned correctly. Therefore, it was chosen to create a new folder inside the folder which contains the testing files (*/mdk/bin/shared*). The new folder is named *'HELPER'*.

The code for these tests serves as the basis of the understanding of the robot. The same programming language (Python) was used for development to build on this comprehension further. Alternatively, the robot is also compatible with C++. In addition to the libraries included in the MDK, the libraries as stated in table G.1 are utilized.

Table G.1: Libraries used to develop the additional code of MiRo.

	version	URL
BLEAK	0.20.2	https://bleak.readthedocs.io/en/latest/
Asyncio	3.4.3	
UUID	1.30	

The developed code can be found and installed via https://github.com/daniquedamen/MiRo. When installed and positioned correctly, the folder will look as shown in figure G.1.

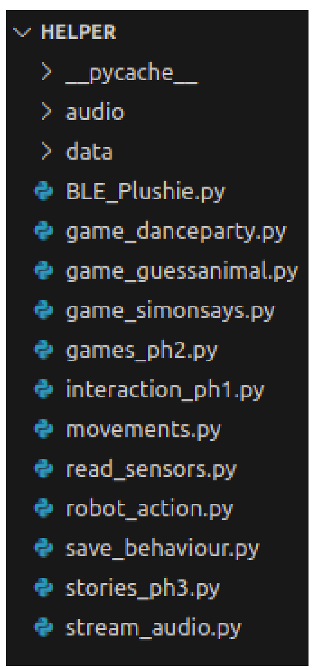
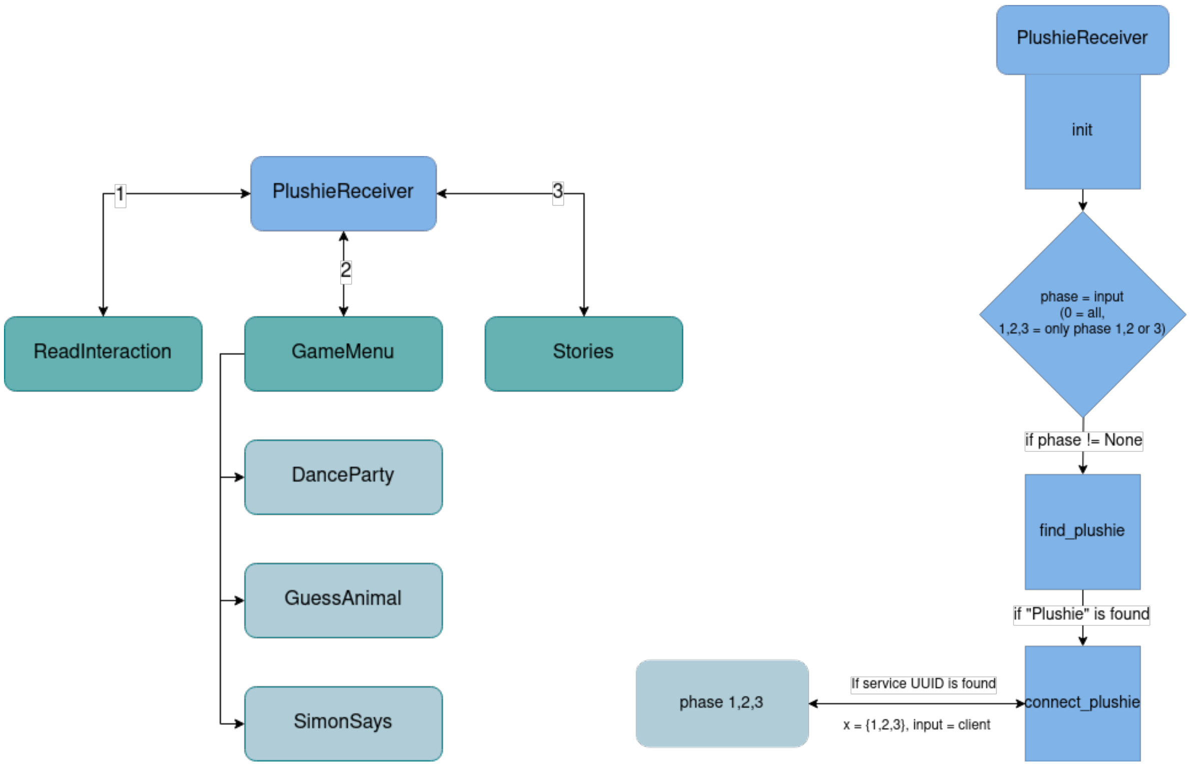


Figure G.1: Files of developed code.

2 Documentation

As Python supports object-oriented programming, the code is structured in classes. Therefore, the documentation holds this structure as well. The code starts in the BLE_Plushie file, which holds the PlushieReceiver class. From this class, the three phases, as seen in figure G.2, are started.



(a) *(b)*

Figure G.2: In the PlushieReceiver Class, the BLE connection is established, and the phases of the tests are started. On (a), the class connection to the phases is displayed, and (b), a simplified flow chart from the class.

2.1 PlushieReceiver

The BLE connection is established within this class and the different phases are started.

As seen in figure G.2, the class is initialised, **init**, first, in which an asyncio event loop is defined. The event loop is used for scheduling co-routines. For more clarification about asyncio and event loops, Appendix 2 can be consulted. Then, the user input is requested to start the whole loop or one phase separately. If user input is obtained, the **find_plushie** function is started as part of the event. This async function uses the bleak library to scan for BLE advertising devices. While no device is defined, it searches for a device named "plushie" is found. This co-routine runs until it is complete so the plushie is found. In the async function **connect_plushie**, the bleak library is again used to interface as the client with the plushie. Since the BLE connection needs to be sustained while executing other tasks, async is used. The time needed to read data from characteristics can vary; therefore, awaits are required to allow performing another task while waiting. When the desired service, including the sensor data, is found, the chosen phase is started while saving this choice, but that will be explained in section 2.3.

Overview phase 1

Each phase uses a variety of common classes. Therefore, a function call graph, figure G.3, is produced for the first class to give an overview. The corresponding sections will describe the similarities and differences for phases 2 and 3. PlushieReceiver class, section 2.1, initialises the Save, ReadInteraction (phase 1), Games (phase 2) and Stories (phase 3) classes. Phase 1 links to the Read_Sensors class and the call_action function, which starts the controller and, therefore, Streamer class. Since the Read_Sensors, Save, Controller and Streamer class will be invoked in every part of the code, these will be elaborated first as the Common Classes. Then, the classes of the other phases will be described.

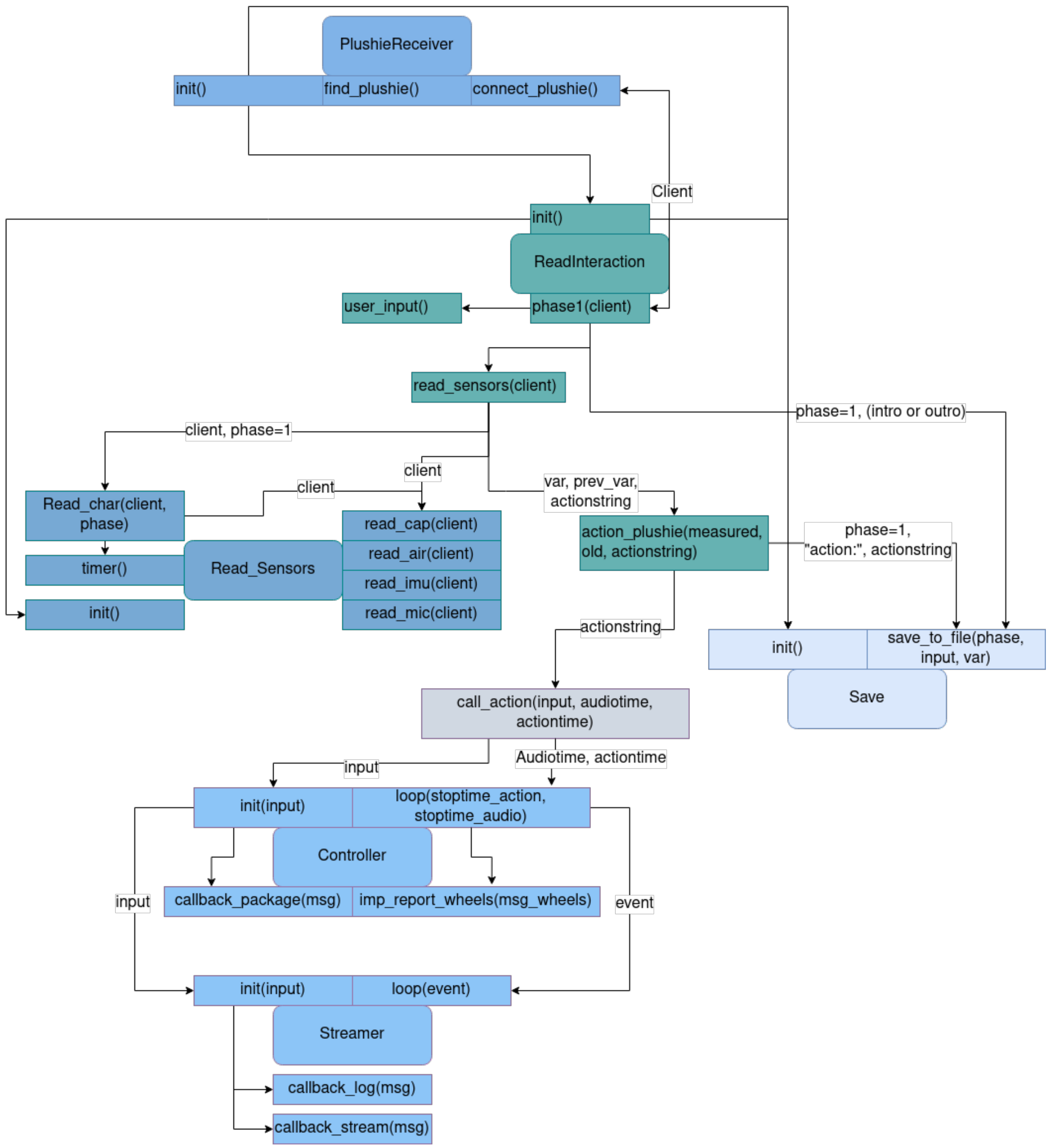


Figure G.3: Function Call Graph of the first phase of the code.

Common Classes

2.2 Read_Sensors

This class can be used to read each sensor's sensor data separately or write the sensor data to a '.csv' file. Thus, the class contains multiple functions to provide this.

Firstly, the **init** of the class defines the UUID of the characteristic of each sensor and initialisation of other parameters.

In the **Read_char(client, phase)** function, the sensor data is written to a CSV file. Therefore, it requires phase as input. This checks whether a file for saving data exists or should be created. When a new file is created, the date and time is documented. Then, the parameter *phasefile* is changed to state that the file is created. When the file already exists, the timer function is called.

In the **timer** function, the starttime is documented and the elapsed time is determined.

Then, the sensor data is requested from the four sensor functions. These functions require the 'client' as their input to interact with the BLE connection. Therefore, the **Read_char** function also needs 'client' as input. Since requesting data over BLE could be unpredictable or relatively slow compared to the execution speed of code, asynchronous functions are used. More detail on Async functions and awaitables is given in Appendix C2. Thus, the read sensor functions are awaited to prevent inefficiency. This means that **Read_char** is also defined as an Async function.

After awaiting the sensor data, the current minutes, seconds, elapsed seconds, peak frequency (mic), the magnitude of the gyroscope (imu), which pads are touched (cap), and air pressure (air) are written to the '.csv' file.

Reading the GATT characteristic is awaited for each of the Read sensor functions. When the data is obtained, the data is transformed back from bytes to integers. The byte order is a little-endian, meaning that the most significant value is at the end of the byte array. Then, an interaction determination is done by comparing the measured data with the threshold. As a return, the functions return 1 in case of interaction. Thus, a general form of a sensor function is as follows:

```
async def Read_Sensor(self, client):
    self.sensor = await client.read_gatt_char(self.sensor_uuid)
    self.sensor = int.from_bytes(self.sensor, 'little')
    if self.sensor > threshold:
        return 1
    return 0
```

The specificity of each function is in its threshold. For **Read_Mic(client)** and **Read_IMU(client)** is now set on 150 Hz and $°/s$. For **Read_CAP(client)**, this is 0 and for **Read_Air(client)** it is 100 Pa. These thresholds are specified after the experiences during experimental testing and are not based on literature.

2.3 Save

This class is supplementary to the Read_Sensors class. Its goal is to document the choices and actions during the experiment. Therefore, the working of the **init** is the same and the working of **save_to_file(phase, input, var)** is similar to that of Read_char. Only **save_to_file** takes the phase, input, and a possible variable to write to file instead of sensor data.

2.4 call_action

call_action(input, audiotime, actiontime) is not a class but a function. This function is used to prevent repetition of code. It takes input as input and initialises the controller class with it. Furthermore, it starts the controller loop with audiotime and actiontime as input which function as the exit times. Then, for a short period of time.sleep is used to prevent possible mix-ups of audio or movements. As default, audiotime and actiontime are 1000 ms.

2.5 controller

With this class, the movements of the robot can be started. It is also linked to the audio class, streamer, to create a common time variable for quitting both actions simultaneously, when needed. Therefore, it also contains the statements for these actions.

In the **init(input)** of the controller, a ROS node, as described in Appendix 3.1, is initialised. Then, the streamer class is initialised. The Publishers and Subscribers are defined and the input is translated to action parameters of the robot as stated in table G.2.

Table G.2: The actions of the robot according to their input. Potential actions are divided into cosmetic (self.cos), kinematic (self.kin), spinning (self.spin) and lights (self.illum).

input	self.cos	self.kin	self.spin	self.illum
ph1_intro	"y"			
ph1_same or ph1_hold	"w"			
ph1_shake	"lrx"	"lyp"		
ph1_talk	"e"			
ph1_squeeze			2.0	
ph1_outro	"ey"			
ph2_congratulations	"lrx"	"lyp"		True
ph2_music1 or ph2_music2	"lrx"	"lyp"		
ph2_sh_x	"w"			
ph2_cat or ph2_dog	"d"			
ph2_donkey or ph2_cow	"dey"			
ph3_intro	"e"			
ph3_1	"d"			
ph3_2 and ph3_5	"yew"			
ph3_3	"w"			
ph3_4, ph3_6	"lrx"	"lyp"		True

The **loop(stopttime_action, stopttime_audio)** function is executed to start movement and audio. First, an event is initiated for threading and the variables current time *curr_time* and *t_now* are created. Then, the function runs while active is True. In this loop, calculations on the movements are executed. Afterwards, the program pauses for 0.02 seconds ($time.sleep(0.02)$) and *t_now* is updated. However, four exceptions exist:

1. when the loop is started, so $curr\_time = 0$, a thread is started to run the audio loop with the event as input.
2. When the default stopttime (1000 ms) is the loop's input, the function should return whenever the audio is ready. Thus, when this is the case (stopttime_action=1000 and audio thread is finished), the head of the robot returns to the origin and the function returns.
3. If the stopttime of the audio is set (so not on default 1000) and the current time has reached the stopttime of the audio, the event will be set which makes the audio exit.
4. When the current time reaches the maximum stopttime, the robot returns to the origin and then returns

When no exception is called, the calculations take place as the calculations are separated in self.kin and self.cos, these are evaluated separately. The parameter is checked for certain letters, and a calculation is executed when the string contains a letter. The actions corresponding to certain letters are stated in table G.3. The theory of the calculations is described in section 4. $self.spin$ and $self.illum$ do not initiate calculations but are directly processed. Afterwards, the resulting message (msg) is published to the corresponding topic.

Table G.3: The kinetic and cosmetic movements according to their letters. Also i for the cosmetic data list is provided as described in section 4.

	letter	**action**	**i**
self.kin	l	lift	
	y	yaw	
	p	pitch	
self.cos	l	left	2,4
	r	right	3,5
	y	eyes	2,3
	e	ears	4,5
	w	wag	1
	d	droop	0

2.6 streamer

The class is initialised, **init**, from the controller class passing the input. The input is transformed to the variable TRACK_FILE, as in table G.4. The path of these files is:

```
TRACK_PATH = "../../../mdk/bin/shared/HELPER/audio/" + TRACK_FILE
```

The audio files are decoded. The content of the audio files is written out in section F.

Table G.4: The audio action tracks from the input from the controller.

Input	Track
ph1_intro	ph1_1.mp3
ph1_same	ph1_2.mp3
ph1_shake	ph1_3.mp3
ph1_hold	ph1_4.mp3
ph1_talk	ph1_5.mp3
ph1_squeeze	ph1_6.mp3
ph1_outro	ph1_7.mp3
ph2_intro	ph2_8.mp3
ph2_choose	ph2_9.mp3
ph2_intro_g1	ph2_10.mp3
ph2_music1	ph2_11.mp3
ph2_music2	ph2_12.mp3
ph2_congratulations	ph2_13.mp3
ph2_nexttime	ph2_14.mp3
ph2_intro_g2	ph2_15.mp3
ph2_sh_donkey	ph2_16.mp3
ph2_sh_dog	ph2_17.mp3
ph2_sh_cat	ph2_18.mp3
ph2_sh_cow	ph2_19.mp3
ph2_sh_lion	ph2_20.mp3
ph2_cat	ph2_21.mp3
ph2_cow	ph2_22.mp3
ph2_dog	ph2_23.mp3
ph2_donkey	ph2_24.mp3
ph2_lion	ph2_25.mp3
ph2_intro_g3	ph2_26.mp3
ph2_a	ph2_27.mp3
ph2_blab	ph2_28.mp3
ph2_hold	ph2_29.mp3
ph2_shake	ph2_30.mp3
ph2_squeeze	ph2_31.mp3
ph2_goodjob	ph2_32.mp3
ph2_next	ph2_33.mp3
ph3_intro	ph3_34.mp3
ph3_1	ph3_35.mp3
ph3_2	ph3_36.mp3
ph3_3	ph3_37.mp3
ph3_4	ph3_38.mp3
ph3_5	ph3_39.mp3
ph3_6	ph3_40.mp3

Then, the **loop** function of the class gets the event initialised as a threading event in the controlled loop as input. The function runs while the event is not set, thus when the current time has not yet reached the stop time of the audio. Then, the audio is played by publishing the msg created to the *pub_stream* topic.

Phase 1

This is a breakdown of the code for test phase 1. However, the test description can be read in section F.1. Some software foundation is given in section C.

2.7 ReadInteraction

The class, including the phase 1-specific code, is named ReadInteraction. The function calls to and from the functions in this class can be seen in figure G.3.

In the constructor of this class, **init**, a list of the discovered sensors and initialisation of the read sensor values.

phase1, the async function called from the PlushieReceiver class, first plays the start of the introduction of the phase. The event loop, which sustains the BLE connection and calls the function, does not allow nested event loops. Nonetheless, the function should continuously check for user input to interfere with the process when needed. However, asynchronous programming is also not an option for this cause since gathering asynchronous functions still does not allow parallel running as desired. Therefore, multi-threading needs to be used [32]. These principles are further described in section C. A thread of **user_input** is started, followed by the execution of the **read_sensors** function under the condition that no user input is given and not all sensors are discovered yet. If this condition is not met, the outro will be played and the function returns to the PlushieReceiver class.

The **read_sensors** async function reads the four sensors and stores the values in the parameters. These are not the measured values of the sensors but the interaction values, so zero or one. Then, a check is executed by the **action_plushie**function to see if there are differences compared to the last measurement. If the measured value is larger than the old value, there was no interaction based on that sensor first and now there is. This particular sensor is not discovered yet, so the actionstring is not in the list, the robot will react responsively. The actions and sensor data are saved to the corresponding files.

Phase 2

This is a breakdown of the code for test phase 2. However, the test description can be read in section 2. Figure G.3 can be inspected for a better overview as this phase's function flow is similar to phase 1. For full clarification, these links are more explicitly mentioned in this section as for phase 1. Some software foundation is given in section C.

2.8 Games

The constructor, **init**, of the main class of phase 2, Games, initialises flags. The classes Save, Read_Sensors and the game-specific classes DanceParty (section 2.8.1), GuessAnimal (section 2.8.2) and SimonSays (section 2.8.3).

The async function **GameMenu** is called from and returns to **connect_plushie** from the PlushieReceiver class. It takes the client, the interface to the server, as input. First, the intro from the GameMenu is started, followed by a flag check of the variable game. Then, a thread is started for the function **user_input**. This continuously checks for user input during the execution of the GameMenu. With user input, the choice for games 1, 2 or 3 can be determined, or the user can decide to input four and quit and return to **connect_plushie**. Then, the following steps are taken:

1. If there is no user input yet, check if the child shook the plushie.
2. If there is no user input and the child shakes the plushie, the robot will ask which game the child wants to play.
3. if there is still no user input, the async function **sensor_input** will read the sensors
4. if there is a choice and the game is not finished yet, **start_game** will be awaited
5. if the finish flag is set, the IMU is awaited to wait to return to the PlushieReceiver class

The async **sensor_input** function waits 3 seconds and then reads the sensors to check if the child shakes, squeezes or holds the plushie to number the game correspondingly. This will also be saved for later insights.

The async **start_game** function translates the number to the start of the game. When the game is finished, it returns a 1 for victory or a 0 if the child loses. Then, MiRo will execute the corresponding outro and set the finish flag.

2.8.1 DanceParty

The Read_Sensors and Save class are initialised in the **init** of DanceParty.
From the **start_game** function, the function **play** is called. The time for the music is determined as a random value between 200 and 800, which leads to a different length of the game each time. The time for the robot to stop dancing after the music stops, robottime, is currently the music time + 100, but this can be further explored to become an appropriate duration. Now, two music fragments are implemented, and one is randomly picked. Then, the robot starts dancing and playing the music for the set duration. When the robot stops, and the child has already stopped dancing, return 1; otherwise, 0.

2.8.2 GuessAnimal

In the GuessAnimal **init**, the current and previous animal, the Read_Sensors and Save class, and a finish flag are initialised.

The async **play** function is called from the GameMenu. First, the robot plays the introduction of the game, after which the **whichone** function is called. Within a random task, 1-5 is chosen, and the robot executes the intro for this task too. Then, the async function **orderofsound** is called. If the sound of the animal of the task has not been played yet, a random number will be picked and the robot will play this sound. A list of previous animals keeps track of sounds that will not be double-played. When the sound of the animal played is equal to that of the task, the function returns.

From **play**, the IMU is read for interaction. If the child shakes the plushie after the correct animal has been heard, it returns 1; otherwise, it returns 0.

2.8.3 SimonSays

From the GameMenu, SimonSays is initialised (init) and the async function **play** is called. First, the introduction is played. Then, five times, a task is chosen in the **tasks** function, and the **Interactioncheck** function is awaited. If this function returns 1, it is a correct answer; otherwise, it is incorrect. MiRo responds to this. If 3/5 answers are right, the function returns 1 to the GameMenu because the child wins the game; otherwise, it will return 0.

In **tasks**, a random number, 1-4, is picked and the corresponding task is presented to the child by MiRo.

The async **Interactioncheck** function takes this task as input and reads if there is interaction with the corresponding sensor. If that is the case, it returns 1; otherwise, it returns 0.

Phase 3

This is a breakdown of the code for test phase 3. However, the test description can be read in section 3. Figure G.3 can be inspected for a better overview as this phase's function flow is similar to phase 1. For full clarification, these links are more explicitly mentioned in this section as for phase 1. Some software foundation is given in section C.

2.9 Stories

The class for phase 3 is called Stories. From PlushieReceiver, **MagicWandStory** is started. First, the introduction is started. Then, the story can be started with user input, requested in **user_input**, or by shaking the plushie.
The **story** function sends the commands for the separate parts of the story to the **call_action** function and awaits the requested specific interaction afterwards.
- first of SS is always wrong

H Observational tool

For analysis, an observation tool is developed. It will be noted when there are changes in the child's behaviour with the corresponding time. This will be used for comparison to the measurement data.

Wellbeing is the state of feeling happy and healthy [1]. A happy child moves energetically, shows affection, is engaging and curious and can express joy through words. Children of the target group (aged 3-5) have difficulty verbalising their likes and dislikes. Therefore, the behaviour of a child is observed.

During the tests, the researcher is provided with a table for each subject, containing the parameters and points of attention, as stated in table H.1, which can used as a template for the notes taken per phase. Further information specified at the start of each experiment is the following: Test person (a number), age and gender.

Table H.1: The observation tool used as a template for notes taken on the child's behaviour during the tests.

Parameter	
Facial expression	Smiling Composed Grimace
Child verbal	Complaints Happy Note
Movements	Legs Arms Other
Behaviour towards technology	Affective Engaging Curious Confidence Frustration Hesitant
Interaction with plushie	Hold Squeeze Shake Mic
Emotion	Content Happy Sad Tired Angry Surprised
Challenges	
Task completion	
Attention span	
Other observations	

I Sensor data

The intensity and frequency of interactions with the plushie are derived to indicate the child's behaviour. Therefore, the peak frequency (microphone), magnitude of the gyroscope (IMU), touch (Capacity pads) and pressure (Air pressure sensor) are measured. Since the order of the phases depends on the choices made, these can vary per child. For analysis, the graphs of the measurements are displayed with indications of each phase. Subsequently, the frequency of the interactions is derived by counting the peaks for each sensor in total and separately per phase. For this derivation, peaks are defined as the data points above the thresholds specified in table I.1. Subsequently, the mean intensity of these interactions is calculated. First, the average of all children is provided in section 1 followed by the results per individual (sections 2-7).

Table I.1: Thresholds for interaction set for the peak frequency measured with a microphone, the magnitude of the gyroscope measured with an IMU and pressure measured with an air pressure sensor.

Sensor	Threshold
Mic	150 Hz
IMU	150 °/s
Air	100 Pa

1 Average

The separate data is complex to analyse. The actual values are not particularly relevant since they depend on much more than stated. What is important is if the interactions can indicate the child's behaviour. Therefore, the results are compared to the average of the tested children. The average amount of interactions per sensor, per phase, is provided together with its total and the average intensity of each interaction in table I.2.

Table I.2: The average of peaks measured with a microphone (Mic), IMU, capacity sensor (Cap) and air pressure sensor (Air) per phase and the average number of interactions for the total tests. These include a test with Dance Party as a game of choice (total_DP) or Guess the Animal (total_GA) or a test only including phases 1 and 3 (total_13).

	Peaks			
Phase	Mic	IMU	Cap	Air
1	3.7	2.7	2.2	2.2
2 Dance Party	0	1.5	2	0.5
2 Simon Says	1.4	1.2	2.8	2.4
2 Guess the Animal	5.3	3.7	3.7	1
3	1.3	3	5.8	4.5
Total_DP	6.4	11.2	11.5	9.6
Total_GA	11.7	13.4	13.2	10.1
Total_13	5.1	5.7	8	6.7
Average intensity	304 Hz	538 °/s	-	868 Pa

The data for the test persons is compared to each average with a margin of 10%. The children could choose Dance Party or Guess the Animal as the second game. It can be noticed that the average number of interactions during Guess the Animal is higher. This could be due to the instructions from the robot. Thus, the total number of interactions per possible test is provided for comparison.

2 Test person 1

Test person one completed the test, including four phases. The approximate duration of the test is 360 seconds. From figure I.1, the peak in frequency in phase 1, pressure in phase 2 and magnitude at the end of phase 2 and start of phase 3 are eye-catching.

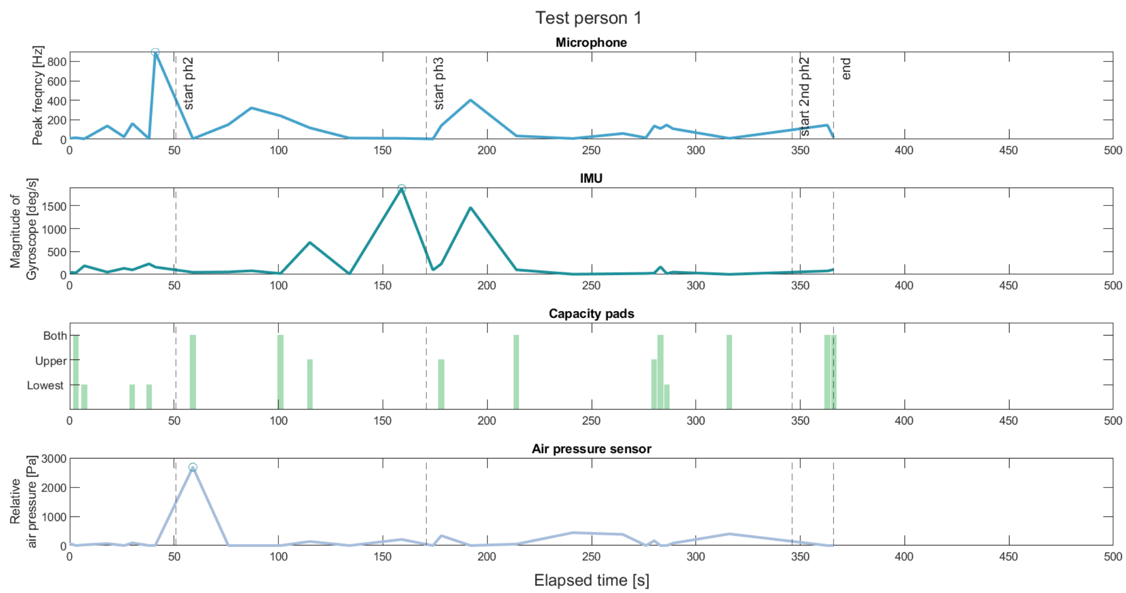


Figure I.1: The data for test person 1. For each test subject, from the top to lowest graph: The peak frequency [Hz] (Microphone), magnitude of the gyroscope [°/s] (IMU), which capacity pad is touched and relative pressure [Pa] (Air pressure sensor) over the elapsed time of the experiment. The start of the phases is indicated with a vertical dotted line, and the maximum value for each sensor is indicated with a dot.

From the frequency and intensity of the interactions, as stated in table I.3, it can be seen that the total intensity of interaction is the highest during Simon Says and lowest during Dance Party. The frequency of interaction is the highest during phase 3, the story. Overall, fewer interactions were observed than average. Additionally, the intensity of the interactions with the IMU and pressure sensor is lower.

Table I.3: The number of peaks and their mean for the microphone (Mic), IMU, Capacity sensors (Cap) and pressure sensor (Air) during each phase for test person 1.

	Mic		**IMU**		**Cap**	**Air**	
Phase	peaks [-]	mean [Hz]	peaks[-]	mean [°/s]	peaks[-]	peaks[-]	mean [Pa]
1	2	527	3	194	4	0	NaN
2 Simon Says	2	281	2	1288	3	3	1010
3	1	403	3	620	6	5	345
2 Dance Party	0	NaN	0	NaN	2	0	NaN
Total	5	404	8	627	15	8	594
Compared to average	-	+	-	-	+	-	-

3 Test person 2

The test, including all four phases, is completed by test person two within approximately 470 seconds. From figure I.2, the peak for the IMU in phases 2 and 3 and a peak in pressure applied in phase 3 are remarkable.

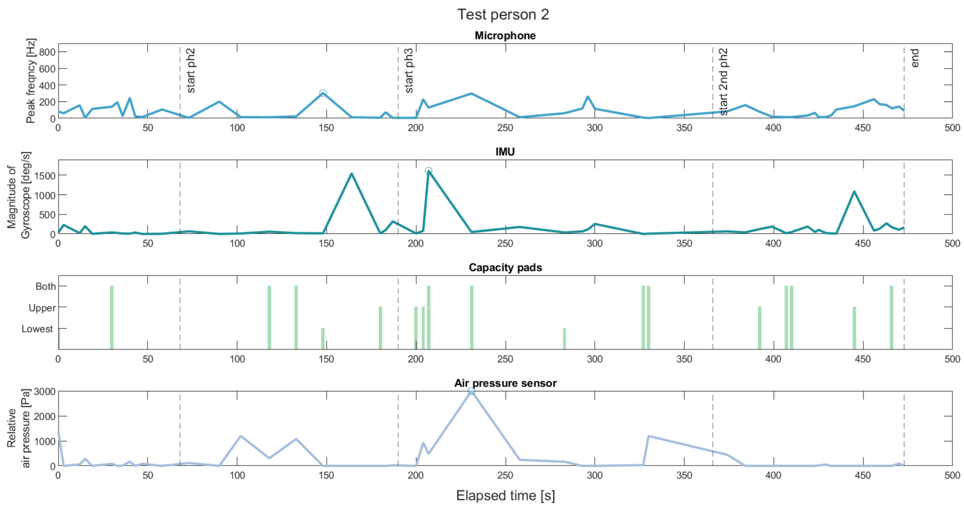


Figure I.2: The data for test person 2. For each test subject, from the top to lowest graph: The peak frequency [Hz] (Microphone), the magnitude of the gyroscope [°/s] (IMU), which capacity pad is touched and relative pressure [Pa] (Air pressure sensor) over the elapsed time of the experiment. The start of the phases is indicated with a vertical dotted line, and the maximum value for each sensor is indicated with a dot.

From the frequency and intensity of the interactions, as stated in table I.4, it can be noticed that the intensity of interaction does not only increase or decrease during the test. The interactions are well spread over the phases. In most cases, the number and intensity of interactions are close to the average.

Table I.4: The number of peaks and their mean for the microphone (Mic), IMU, Capacity sensors (Cap) and pressure sensor (Air) during each phase for test person 2.

	Mic		**IMU**		**Cap**	**Air**	
Phase	peaks [-]	mean [Hz]	peaks[-]	mean [°/s]	peaks[-]	peaks[-]	mean [Pa]
1	3	198	2	216	2	3	615
2 Simon Says	2	252	1	1546	3	4	673
3	3	262	4	592	8	6	1000
2 Guess the Animal	4	180	5	381	5	1	445
Total	12	217	12	521	18	14	784
Compared to average	=	-	=	=	+	+	=

4 Test person 3

As displayed in figure I.3, the approximate duration of the completed test for test person three is 470 seconds. The amount of interaction in phase one is most striking.

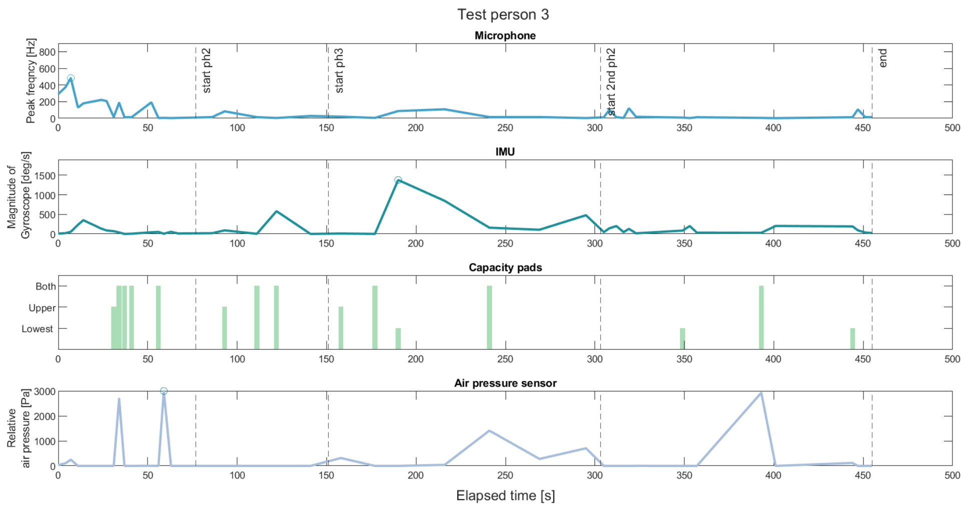


Figure I.3: The data for test person 3. For each test subject, from the top to lowest graph: The peak frequency [Hz] (Microphone), magnitude of the gyroscope [°/s] (IMU), which capacity pad is touched and relative pressure [Pa] (Air pressure sensor) over the elapsed time of the experiment. The start of the phases is indicated with a vertical dotted line, and the maximum value for each sensor is indicated with a dot.

From the values stated in table I.5, the absence of peaks in the microphone data, besides in phase 1, is notable. Additionally, the total number of interactions in phase 1 is outstanding compared to the other phases. The number of interactions is always close to or larger than average. Nevertheless, the mean intensity of the interactions with the microphone and IMU is smaller.

Table I.5: The number of peaks and their mean for the microphone (Mic), IMU, Capacity sensors (Cap) and pressure sensor (Air) during each phase for test person 3.

	Mic		**IMU**		**Cap**	**Air**	
Phase	peaks [-]	mean [Hz]	peaks[-]	mean [°/s]	peaks[-]	peaks[-]	mean [Pa]
1	8	267	2	293	5	4	1511
2 Simon Says	0	NaN	1	582	3	0	NaN
3	0	NaN	4	716	4	4	676
2 Dance Party	0	NaN	3	203	2	1	2925
Total	8	267	10	464	14	9	1297
Compared to average	+	-	=	-	+	=	+

5 Test person 4

As displayed in figure I.4, the test duration for test person 4 was approximately 500 seconds. There are no discrepancies in the phase order. The number of interactions with the capacity sensor seems low. For the other sensors, no clear pattern for the frequency of interactions can be noticed.

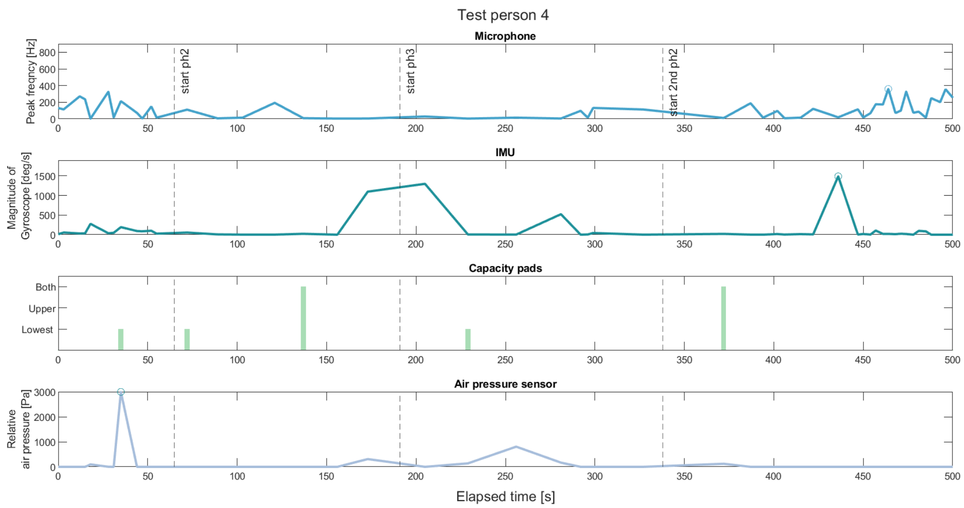


Figure I.4: The data for test person 4. For each test subject, from the top to lowest graph: The peak frequency [Hz] (Microphone), the magnitude of the gyroscope [°/s] (IMU), which capacity pad is touched and relative pressure [Pa] (Air pressure sensor) over the elapsed time of the experiment. The start of the phases is indicated with a vertical dotted line, and the maximum value for each sensor is indicated with a dot.

From table I.6, the number of interactions seems well spread too. However, these are slightly higher for phase 1 and Guess the Animal. No clear pattern is observed in the intensity of the interactions according to the phases. The number of interactions is smaller than average, except for the microphone. The intensity of these interactions is not very high, below average for the microphone and pressure sensor.

Table I.6: The number of peaks and their mean for the microphone (Mic), IMU, Capacity sensors (Cap) and pressure sensor (Air) during each phase for test person 4.

	Mic		**IMU**		**Cap**	**Air**	
Phase	peaks [-]	mean [Hz]	peaks[-]	mean [°/s]	peaks[-]	peaks[-]	mean [Pa]
1	4	261	2	235	1	1	2996
2 Simon Says	1	193	1	1098	2	1	310
3	0	NaN	2	911	1	3	371
2 Guess the Animal	8	254	1	1489	1	1	122
Total	13	251	6	813	5	6	757
Compared to average	+	-	-	+	-	-	-

6 Test person 5

Test person 5 chose to deviate from the standard order of phases. The child did not want to play a game. Therefore, as seen in figure I.5, the test duration is only approximately 260 seconds. The intensity of interactions is higher during phase 3 than phase 1.

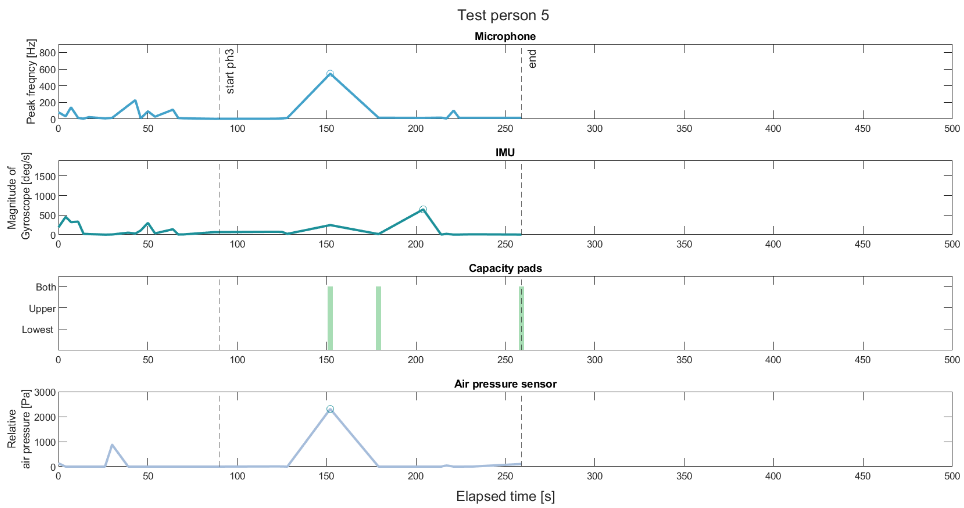


Figure I.5: The data for test person 5. For each test subject, from the top to lowest graph: The peak frequency [Hz] (Microphone), magnitude of the gyroscope [°/s] (IMU), which capacity pad is touched and relative pressure [Pa] (Air pressure sensor) over the elapsed time of the experiment. The start of the phases is indicated with a vertical dotted line, and the maximum value for each sensor is indicated with a dot.

Table I.7 shows that the intensity of the interactions during phase 3 is more significant than during phase 1, but the amount of interactions is not. The intensity of the interactions is always equal to or smaller than average. The number of interactions is also below average, except for the IMU.

Table I.7: The number of peaks and their mean for the microphone (Mic), IMU, Capacity sensors (Cap) and pressure sensor (Air) during each phase for test person 5.

	Mic		**IMU**		**Cap**	**Air**	
Phase	peaks [-]	mean [Hz]	peaks[-]	mean [°/s]	peaks[-]	peaks[-]	mean [Pa]
1	2	195	5	320.6	0	2	503.5
3	1	545	2	446.5	3	2	1207
Total	3	312	7	357	3	4	855
Compared to average	-	=	+	-	-	-	=

7 Test person 6

Test person 6 completed the test in the standard order in approximately 500 seconds. From figure I.6, it can be noticed that the interactions with the capacity pads are well-spread. The peaks in phase one and during Guess, the Animal, are outstanding for the pressure sensor.

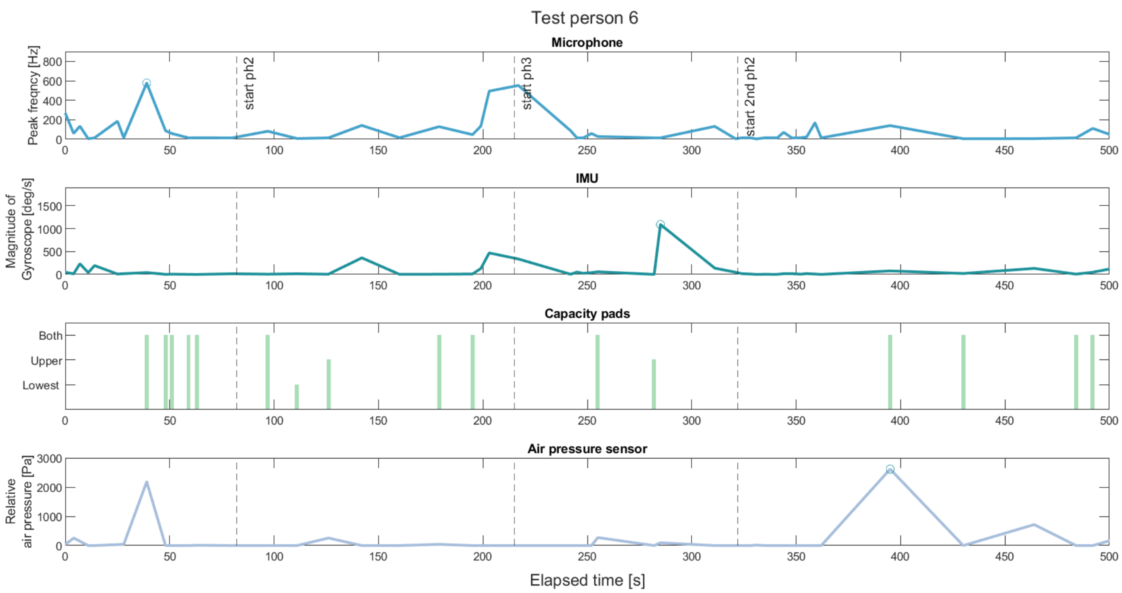


Figure I.6: The data for test person 6. For each test subject, from the top to lowest graph: The peak frequency [Hz] (Microphone), magnitude of the gyroscope [°/s] (IMU), which capacity pad is touched and relative pressure [Pa] (Air pressure sensor) over the elapsed time of the experiment. The start of the phases is indicated with a vertical dotted line, and the maximum value for each sensor is indicated with a dot.

The overall frequency and intensity per phase seem similar, looking at the summary of the peaks and mean, as stated in table I.8. The amount of interactions is below average, except for the capacity sensor. The intensity of the peak frequency and pressure is above the mean, while the magnitude of the gyroscope is below.

Table I.8: The number of peaks and their mean for the microphone (Mic), IMU, Capacity sensors (Cap) and pressure sensor (Air) during each phase for test person 6.

	Mic		**IMU**		**Cap**	**Air**	
Phase	peaks [-]	mean [Hz]	peaks[-]	mean [°/s]	peaks[-]	peaks[-]	mean [Pa]
1	3	344	2	214	5	3	863
2 Simon Says	1	494	2	416.5	5	1	257
3	1	552	2	714	2	1	273
2 Guess the Animal	1	169	0	NaN	4	2	1667
Total	6	375	6	448	16	7	922
Compared to average	-	+	-	-	+	-	+

J Transcription observations

On location, the children tested the technology in the setup, as seen in figure J.7. During the tests, the pedagogical scientist (on the right) observed the children with the tool, table H.1, designed for these tests. These notes are translated into the profiles of the children as described in this section.

Figure J.7: The pedagogical scientist observed the children while they were playing with robot MiRo.

1 Test person 1

5.5 years old, really enthusiastic and energetic

The robot was not ready yet when a very enthusiastic child of 5.5 years old, came into the room. They had to wait a little but seemed very excited. They were curious and focused and listened carefully to the robot. They understood the commands from the robot regarding the interactions with the plushie. When the story was played, they did not seem really very interested. Afterwards, they got excited and energetic when they were allowed to do another game.

2 Test person 2

5 years old, clever and chatty

Test person 2 was a 5-year-old child. They immediately started talking about their father, who also worked in Robotics, and told us they had skipped a year in school. They seemed very intelligent for their age. They found the robot really cool and were paying close attention. When the robot started talking, they started giggling. There was background noise, which prevented them from hearing the robot correctly. The twinkling in their eyes made them seem happy. During the game, Simon Says, they appeared determined and curious since they were looking at MiRo and responding very quickly to its commands. During the story, they showed a little smile. During the second game, they could not hear it properly but still seemed focused and confident. Their eyes twinkled when MiRo said, “Good job!” or “Congratulations”.

3 Test person 3

5 years old, calm and reserved
Then, a five-year-old child was called into the room. They were more calm than the test person 1 and 2. They did not seem very shy, as they were not hesitant to answer questions. Nonetheless, they did come off as a little nervous. When the robot started talking, they moved backwards and looked at the researchers. It seemed to have scared and overwhelmed them. The instructions seemed hard, which is why the second phase was started. They seemed more relaxed during the game and kept eye contact with MiRo. During the game, a cautious smile and gloat were seen on their face. They were focused on the robot and its instructions. However, they sometimes looked at the researchers and waited for verbal confirmation or assistance. During the next phase, they really opened up and seemed to enjoy the test. They looked happy and responded enthusiastically to the commands while repeating some words of MiRo. Afterwards, they also notified that they liked the stories the best.

4 Test person 4

4 years old, humoristic and focused
The next Robot tester was a patient child of 4 years old. They were not as energetic as test persons 1 and 2 but seemed enthusiastic nonetheless. They laughed loudly when MiRo turned itself around. The "Hold" was difficult; thus, the next phase was started manually. During the game in phase 2, they were full of concentration. They slightly smiled when the robot complimented them on executing the commands correctly. They pulled their shoulders when MiRo mentioned that the order was incorrectly followed. During the next phase, they did not seem very interested, although they did pay attention. Afterwards, when the next game started, they were still very concentrated and laughed loudly at the animal sounds that were played. They told us that they really liked the games.

5 Test person 5

4.5 years old, expectant and shy
The next participant was a little bit expectant child of 4.5 years old. When MiRo turned around, they got a bit scared and moved slightly backwards. This did not last long, as they soon looked very amazed and curious. A big smile was observed when the robot said, "Now we are going to do something fun!". However, they decided they did not want to play a game but liked to hear the story. In general, they looked a little tight and did not always seem to understand MiRo's commands. Despite that, they seemed to relax a little more during the tests, and their understanding of MiRo's orders grew on them. Large movements of MiRo still surprised them. After the story, they acted very shy again and decided to leave.

6 Test person 6

4.5 years old, amazed but expectant
Lastly, we were told that our last robot tester might not want to participate. They are a very shy child of 4.5 years old with parents with a migration background. Thus, they do not speak Dutch very well. Since they still speak a bit of Dutch and the level of Dutch in the test was not very high, it was decided that the child could still participate while taking this as a side note. They looked very amazed and smiled carefully during the first phase. They repeatedly looked at the researchers for confirmation and instructions. The instructions were provided by communicating verbally and non-verbally. They were intrigued as they had their mouth slightly open. During the game, they listened and switched their attention between MiRo and the magic wand. When MiRo moved, their eyes widened, making them seem involved and curious. During the story, they switched their gaze all over MiRo. They were very intrigued by MiRo even though they did not seem to understand the story completely. During the story, they had a sparkle in their eyes. They seemed expectant and required these little extra instructions. They wanted to do an extra game as well. While listening to the animal sounds, they waited patiently and laughed cautiously.

K Prototype evaluation

The different aspects of the plushie are evaluated. This starts with assessing the sketched scenarios, followed by each part of the plushie separately.

1 Scenario's

The situation of testing is completely different from the scenario's written. The children testing the plushie and robot are healthy and not hospitalised, so questions regarding pain are not included in the MiRo software. The plushie cannot be tested on comforting the child when it is in pain. Another difference is that physiological measurements and the history between children and technology were left out of the research's scope.

The alignments from the scenarios to the testing situation are that the children were keen to hold and interact with the plushie. The sensors captured the child's behaviour to which the robot could respond.

2 Appearance

For its appearance, a magic wand was chosen. However, this might not be the most huggable form for the plushie. Therefore, future research should investigate a huggable form for the plushie in which its functionalities can remain. Also, the possibilities for personalising should be taken into account. The benefits of the magic wand that were noted were the natural behaviour of the child with it. The child holds it constantly and understands that the interactions with the magic wand cause the robot to react. Therefore, it does suit a storyline between both.

3 Hardware

The value of the sensors' data would increase when a baseline for each child can be obtained individually. This can be done during the pre-operative history of a child with the robot and plushie. This baseline can serve as a reference for the measurements obtained per child.

In the designed circuit, the sensors are not entirely free from interference. This should be investigated and prevented for accurate measurements.

4 Sensor limitations

4.1 Microphone

The microphone measures the sounds in the room. Currently, there is no filtering applied to only count the child. Additionally, the peak frequency was used to state if there was any interaction. The room where the measurements were taken was very noisy, so it was hard to evaluate the data obtained. Therefore, further assessment of the functionalities of the microphone should be done. The microphone data processing could be enhanced by using the magnitude of the sound and possibly sound, voice or crying identification.

4.2 IMU

The IMU measures movements well enough. The movements can be captured more accurately by combining the acceleration and gyroscope and processing this data.

4.3 Capacity pads

The capacity pads do not function optimally. This can be seen in the data as the test persons constantly had the plushie, but this is not observed. The reason for this could be the fabric on top of it, the attachments of the wires or the sensor itself. Therefore, this should be solved to optimise the data obtained by these sensors. Furthermore, the sensors should surround the entire plushie to represent how the child is holding the plushie accurately.

4.4 Pressure sensor

As seen in the results section I, the air pressure measures a maximum value of $2996[Pa]$ three times. After investigating this, it was noticed that this was due to hardware limitations. Choosing a balloon with an integrated pressure sensor worked with limitations. First, when the balloon is squeezed, it takes time to deflate again and during this period, the sensor cannot measure accurately. This could be prevented by embedding a pump or using a fully closed system. The balloon with cotton felt more enjoyable than the experimental prototype made with silicon. Therefore, the material of the plushie should be investigated as well. The chosen sensor often reached its maximum measured value, which could be slightly bypassed with software tricks, but it would be better to select another pressure sensor with a more extensive pressure range.

5 Software

The software that was designed is not without bugs. A larger problem noticed is the measurements' inconsistent timing and low frequency. The data is measured within the plushie once per 500 ms but obtained approximately every 4 seconds. This is due to the workings of asynchronous programming. When the data of a sensor is awaited, the rest of the event is continued. When the sensor data is obtained, the rest of the event is finished before it will request sensor data again. Therefore, the delay in obtaining sensor data is caused by the duration of the rest of the function instead of at given time instances. This is a limitation of the BLE connection since the time needed for writing and reading data from characteristics is not set with this connection. An event loop can not be created in another event loop and Async functions can not be threaded easily. Therefore, a solution to this problem has not been obtained yet, and the data is not continuously written to the CSV file.

A smaller issue was that the same command could be given multiple times in a row because of the randomised orders in the game Simon Says. It would be easy and nice for children to set a maximum of two on the same command since it was seen that otherwise, they lose motivation and interest. This is also the case when they have to wait too long for a reaction from MiRo after an interaction. Therefore, the timers/delays should be evaluated.

Another improvement possibility is within the game menu. In the game menu, user input and sensor data are awaited. However, reading the sensor data is too close to the notification of which movement corresponds to which game. Therefore, this often results in the Simon Says game, which starts when the IMU and pressure sensor do not measure interaction, but the capacity pads do.

Smaller points of attention for software improvement are the consistent use of variable names. Lastly, at one time, the robot played two mp3s simultaneously. This bug should be investigated and fixed.