Children's Exploration with Social Robots in Digital Art Making

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Abstract

Exploration is an essential way for children to make sense of the world and reflect on self-identity in the view of constructionism. With materials provided by culture and surroundings, children explore and act in the unknowns in order to understand them. Nowadays, the digital age has created a large variety of technical artifacts that children interact with and provided new environments for them to explore and learn.

Existing technologies have been utilized for children's learning and personal growth. Particularly, artifacts with various levels of anthropomorphism are widely researched in the education domain. On the one end of the spectrum are social robots, which have a higher level of autonomy and more complex underlying mechanisms. They are commonly used as children's companions and provide social support for learning activities in school or at home. On the other end of the spectrum are animated objects with more abstract shapes and less autonomous behaviors. Many of them are built on the learning theory of constructionism and invented for children's creative activities such as drawing and storytelling.

This thesis is particularly interested in using social robots in the domain of art making. Different from the objects with abstract forms in the prior work, the robot examined here has a more anthropomorphic look and animated behaviors. In comparison with skill development and subject learning that are commonly researched for social robots, this thesis aims to stimulate children's exploration and curiosity in art creation. The hypothesis is that children may act differently with more willingness to explore uncertainties in art with the life endowment for the robot.

Here an augmented system with a social robot is designed and implemented that engages children in digital art making activities. On a projected floor, children interact with a mobile robot Kuri with movements and explore the underlying mechanisms of robot behaviors. Further, the thesis investigates robot social behaviors displayed with its facial expressions, body movements, sound and light, and designs experiments to evaluate their effects on children's exploration of uncertainties in the interactive process.

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Chapter 1

Introduction

Exploration is to act in an unfamiliar environment and discover things that are unknown before. In the view of constructionism, children make sense of the world by constantly exploring and interacting with the tangible artifacts in the surroundings [1]. With the materials provided by culture and surroundings, they explore, build, make connections of the unknowns with things that they are familiar with and construct knowledge at different age stages. It is the encounter with other creatures or things in the environment that children reflect on their own identity, rethink who they are and how they differ from others.

New possibilities of exploration arise as the digital age provides artifacts in both digital and physical forms that children interact with, which could have the potential to benefit children's personal growth. Back in 2005, developmental psychologist Edith Ackermann has investigated children's exploration with animated toys with varying degrees of autonomy [2]. The toys presented by Ackermann react to the environment such as moving towards to a certain goal, thus appear to have their own wills. These features are not obvious at the first sight, but children have to experiment again and again in order to find out the hidden mechanisms of these toys. Ackermann suggests that "the artificiality, believability, conviviality and otherness" of these animated toys afford children's exploration of psychological issues such as agency, control and communication [2]. Namely, when children explore the underlying features of these animated toys, they relate their experience with the toy's world, rethink their own relationship with the surroundings and reflect on self-identity.

Children tend to attribute life features to artifacts and these objects with life endowment could motivate children to become more proactive in the activities with the potential to benefit their personal or cognitive development. Nowadays, various technical artifacts are developed for children and some are built with complex decision-making abilities. One example is social robots. Roboticist Cynthia Breazeal defines social robots in this way [3]:

> "As with living things, their behavior is a product of its internal state as well as physical laws. We refer to this class of autonomous robots as social robots, i.e., those that people apply a social model to in order to

interact with and to understand."

What is essential here is that the social model of the robot is perceived and accepted by the user. Such a robot social model from the user's perspective is possible to change qualities of human robot interaction and help the robot performs tasks better.

Social robots for children have been widely investigated, especially in the education domain. Previous research has shown that children treat robots as social entities with agency in between machines and people [4]. They respond to social cues of robots in similar ways that they respond to people. Social robots have been used as educational tools that supplement the current practice. In a study with children from 3 - 8 years, researchers find that children build rapport with a social robot with speech entrainment and self-disclosure behaviors [5]. The rapport with robot contributes to children's success of storytelling and engagement in the interaction. Social robots are also used in areas such as learning second-languages [6, 7], logical thinking [8], building children's growth mindset [9], increasing curiosity [10] and so on.

This thesis is particularly interested in social behaviors of the robot for children's exploratory activities. It presents an augmented system in a projected space with a social robot to engage children in art creation. The research question asked here is how the social behaviors of the robot would affect children's willingness to explore in digital art making activities. Different from Ackermann's animated toys, the robot used in the system has a more anthropomorphic appearance and a higher level of perceived animacy. In comparison with the school-subject learning goal, the interaction aims to develop children's intrinsic personal characters in a non-school setting. It is expected that the result and analysis relating to robotic social behaviors could be generalizable to other scenarios in education. The methods consist of interaction design, system implementation and user study, which are summarized in following paragraphs.

The interaction is designed to engage children in exploring the uncertainties in digital art making on a projected floor. The interaction space consists of a Kuri robot and a top-down projector. The Kuri robot used here can express social cues such as smile and eyes blinking. In the one-on-one interaction session, the participant enters the projection area to interact with the mobile robot as well as the dynamic visual elements on the floor. Two design concepts are proposed, one is abstract art making with the robot moving patterns and the other one is gamified interactive palettes. For the first design, the participant triggers the robot's patterned movements in order to create drawings with robot trajectories. Upon generation, the pattern would float on the canvas until the participant fixes it to form the desired composition. For the second design, the participant chooses one palette out of the multiple choices where each palette has its own theme and interaction mode with the robot. Children are expected to explore the hidden mechanism in each palette that is related to the robot's motion and graphics generation rule. This interaction design aims to provide a playful space for the children to explore. Due to the time limit, only the first design concept is implemented in practice.

The interactive system is implemented with three main components, namely tracking, robotics control and computer graphics. The tracking algorithm constantly sends out robot poses and human poses. It is implemented with a Kinect camera and an IMU sensor on the robot. The robotics controller is built with ROS (Robot Operating System), which controls the robot's autonomous navigation, patterned movements and social animations. It receives the tracked robot poses and human poses in order to decide robot behaviors. The computer graphics system is implemented with openFrameworks, a C++ library based on OpenGL. It generates dynamic visual effects as well as serves as an interface for the participant to interact with the system.

In order to investigate the research question "How would social behaviors of the robot affect children's willingness to explore in digital art making activities?", a controlled user experiment is designed with two conditions by varying the robot's social behaviors. However, the user study is postponed due to the city lockdown during COVID-19 and no human subject study is conducted at this point. The planned user study venue is Sharpsbrugh Community Library in Pittsburgh and user recruitment and study will be scheduled once the library reopens. In Chapter 5, the experiment design is discussed in details.

In summary, the thesis presents an interactive system with a social robot that engages children in digital art making activities. The goal is to investigate children's willingness of exploration when facing uncertainties in a new environment. Two interaction design concepts are proposed with one implemented in practice. The system is built with tracking, robotics control and interactive computer graphics in C++ using ROS (Robot Operating System) and openFrameworks. Further, the thesis develops an experiment protocol with IRB approval to evaluate children's behaviors regarding the research question.

Chapter 2

Related Work

2.1 Constructing Knowledge

"What it means to be knowledgeable, intelligent, experienced, and what it takes to become so?" This question was asked by Edith K. Ackermann back to 2004 [11], who is a developmental psychologist and held a developmental view on children's learning. In her opinion, children learn by experiencing. They make sense of the world through the tangible artifacts they interact with in the surroundings. In another paper[12], she stresses an indirect approach to teaching and suggests that environments should be designed to foster self-directed or collaborative learning.

Ackermann mentions three figures, Jean Piaget, Seymour Papert and Lev Vygotsky, who builds the foundations of learning theory from a developmental perspective [11]. Piaget comes up with the theory of constructivism, that argues children construct knowledge through actions and they are the builders of their own cognitive tools. In the view of constructivism, the environment of learning, the media and objects that children interact with are the key factors for their learning and personal development. In the discussion of Piaget's theory, Ackermann suggests that a good teacher should be the one that "helps learners explore, express, exchange and ultimately expand their views within".

Seymour Papert uses Piaget's constructivism as basis and proposes the theory "constructionism" for children's learning with the focus on technology tools in digital age[13]. In a simple catchy description, constructionism means "learning-by-making" [14]. He views children as builders in the culture where the environment provides materials for them to build with. In the building process, children learn by making connections with things they are familiar with. Papert creates Logo turtle robot, which moves on paper with markers attached on it. Children are able to draw different shapes on paper by programming the Turtle with Logo language. Papert's intention is to invent "objects-to-think-with" and provide a playground for children to explore and learn in digital age. "There is an intersection of cultural presence, embedded knowledge, and the possibility for personal identification"[1].

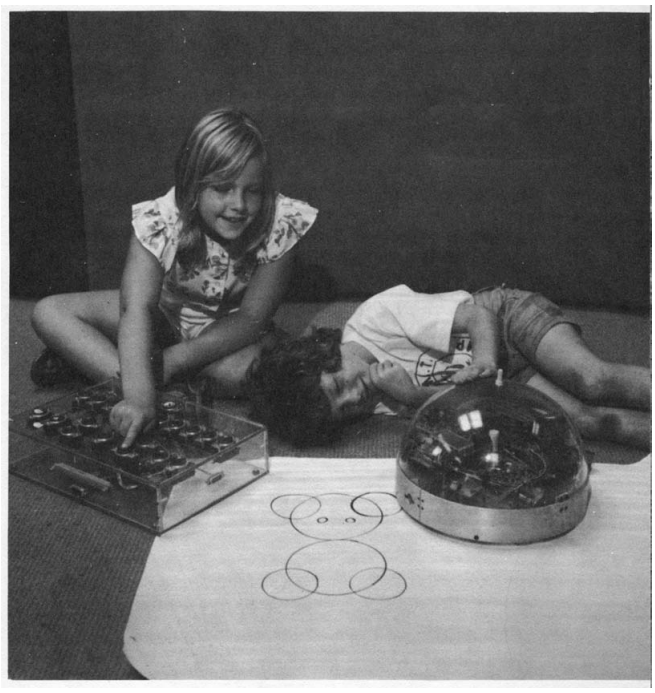


Figure 2.1: A photography of children programming logo turtle to draw [13]

In programming the turtle, children not only learn about technology, but also explore ideas in other domains that no one has taught them in this activity. In children's practice with the Turtle, they are self-motivated to test out different concepts with programming and creates shapes revealing characteristics in mathematics, aesthetics, music, physics, linguistics, etc. As a result, children obtain new knowledge in a natural way, just as they learn to speak.

Papert suggests that two kinds of thinking for children are emerged in such building process: "combinatorial thinking", which explores all possible states of a system and strengthens children's systematic minds, and "self-referential thinking", that children are more reflective and self-conscious in the experimentation process. The "constructionism" approach of learning provides children with new opportunities for growing both emotionally and cognitively.

While the current education curriculum always lists rubrics for knowledge and skills in particular subjects, lots of attention on children's education is about their growth in intrinsic characteristics such as creativity, risk taking, self-confidence, motivation, etc. Seymour Papert points out that technology could provide new possibilities to change the learning environment from the traditional way that passes on knowledge from teachers to students [15]. Instead of memorization via reading and writing, he proposes the natural way humans learn in non-school settings, which provide richer contexts for learners to explore and make connections with things they are familiar with. Using technology as the tool, learners take charge of their own learning. Meanwhile, this process enables children to get access to knowledge in other domains and encourages them to take responsibility and be creative. As described by Papert, "the connectedness and continuity is regarded as powerfully conductive to learning"[15]. With similar goals, art educators view art as a way to build connections to the surrounding world and make meanings. "Art, in its

form, unites the very same relation of doing and undergoing, outgoing and incoming energy, that makes an experience to be an experience." Described by John Dewey in Art as Experience [16], art is a spontaneous, uncontrollable process, while reflective and accumulating.

Both art and technology have the potential to foster characteristics in children's personalities with the focus on the spontaneous interaction process. This has driven this thesis to design and build such an environment for children to explore and make meanings in art with technology artifacts.

2.2 Social Robotics

2.2.1 Brief History of Social Robots

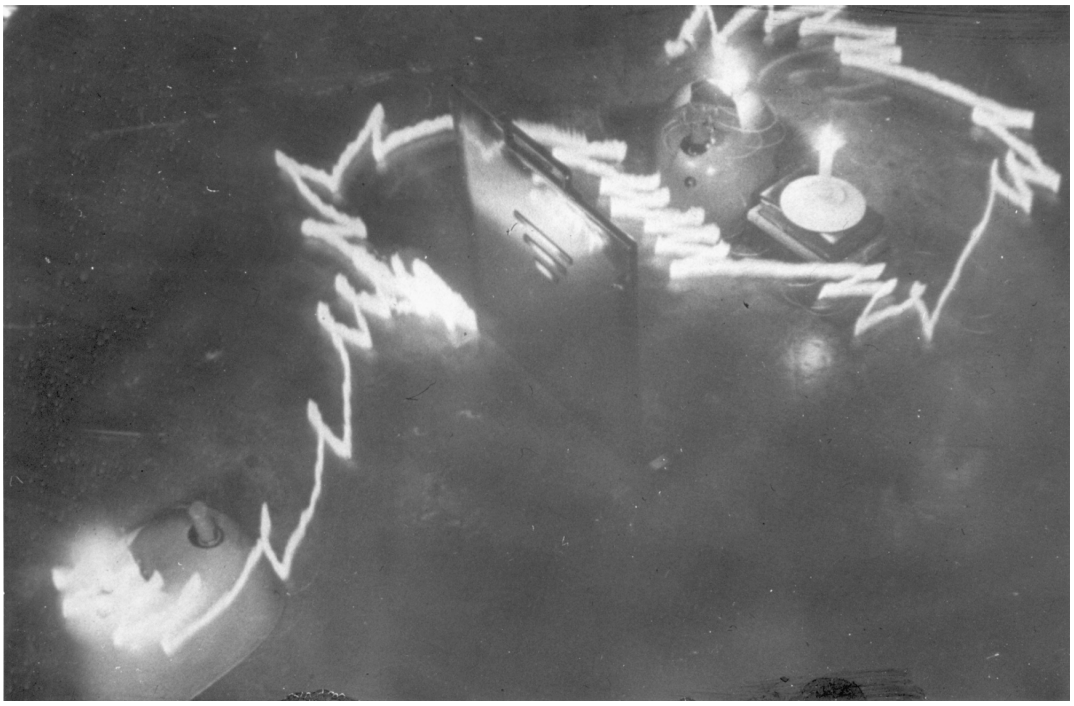


Figure 2.2: A photography of the two tortoises taken at Grey Walter's house in 1940-1950. Candles are mounted on the back of the robot and trace their trajectories

Traditionally "social robots" refer to a group of robots interacting with each other in a seemingly social manner. In 1940s, Grey Walter developed two tortoises that forms a cooperative and competitive relationship [17]. The two robots are released in a dark environment at a distance who attract each other when they are far apart. Once the two robots get close and touch, they repel from each other and move away. This mechanism creates circular movements for the two robot turtles as if they are dancing partners. Such perceived social features come from simple movements and drive people to attribute agency to the two turtle robots as they relate the robot behaviors to social activities in their real life.

As more advanced technology emerges, biologically inspired robots are developed and "social robots" are commonly used for robots that produce complex behavior patterns such as foraging and flocking [18]. These robots with collective behaviors are developed to model animal social society such as ants and swarms. In addition to robots with group social behaviors, another class of social robots emphasizes each individual's feature and capability to engage in social interactions with people. In late 1990s, Dautenhahn Kerstin refers "artificial social intelligence" as an instantiation of human-style social intelligence in artificial agents [19]. In "Towards Social Robots" [3], Cynthia Breazeal suggests such definition for social robots:

> "As with living things, their behavior is a product of its internal state as well as physical laws. We refer to this class of autonomous robots as social robots, i.e., those that people apply a social model to in order to interact with and to understand".

Such type of robots is perceived to have social features from the user's perspective and may change user performances in comparison with their interactions with ordinary machines. Previous research has suggested a list of characteristics for robots to appear to be social [18]:

- express and/or perceive emotions
- communicate with high-level dialogue
- learn/recognize models of other agents
- establish/maintain social relationships
- use natural cues (gaze, gestures, etc.)
- exhibit distinctive personality and character
- may learn/develop social competencies

Though people may have varying levels of expectations on machines' capability of being social, this list provides a reference of robot features contributing to the social model perceived by users. Particularly, the Kuri robot used in this thesis utilizes two elements from the list to exhibit its social behaviors, i.e. "use natural cues" and "learn/recognize models of other agents".

2.2.2 Social Robotics in Education

Previous research has found that children think of robots in between the live, animate beings and inanimate objects [4]. During long-term interaction with robots, children tend to build social-emotional relationships with robots. They display social behaviors to the robot such as sharing gaze, disclosing information, and turn-taking in the similar way that they interact with people [20].

With the life endowment to robots by children, prior research has used a social robot Minnie as an educational tool to aid children's interest development in science learning [21]. This research is built on the importance of social supports and meaningful social interactions during learning activities. It demonstrates the effectiveness of using a social robot in a home environment where children mostly study alone. The robot performs as a science reading companion for 10-12 years children and aids them to generate situational interest in science learning at home. The situational interest is defined as "momentary psychological state during engagement, evident from observed increases in focus and attention" in psychology. The research compares robots in two conditions, i.e. socially adept robot and socially neutral robot. In the social condition, the robot behaves with expressive speeches that give comments on children's reading, exhibits nonverbal cues with eye contact and gaze avert, as well as provides personalized feedback by calling the child by their names, referring to itself as a partner and generating comments based on children's preferences. The result shows that children interacting with the socially adept robot report higher level of closeness and mutual liking for the robot, and show higher situational interests in the reading experience.



Figure 2.3: A child read a science book with Minnie Robot. [21]

Another research investigates preschool children's learning, rapport and emulation of the robot's language during storytelling [5]. This research uses Dragonbot robot as a storytelling companion where children and robot take turns to tell stories about a scene. The robot has animated body movements, facial expressions displayed on a smart phone, plays sounds or speech. Built on the social learning theory that children learn by observing and imitating others, the research examines two modes of the social robot. In one mode, the robot plays stories using words slightly more advanced than children's language skills, while in the other mode the robot uses words not matching children's skills. The result shows that children demonstrates greater vocabulary learning and language emulation when they interact with the robot telling stories with slightly more advanced words. Besides, the research finds that children with higher rapport with the robot are more likely to emulate robot's language, use its keywords and phrases, which leads to better language learning result.



Figure 2.4: A photography of a girl telling stories with a Draongbot robot. [5]

Taken together, the above related work uses robots as a supplement tool for education in informal learning scenarios. The robots exhibit social behaviors such as facial expressions, speeches and body movements that may increase robot animacy and enhance the social relationship formation. Children's learning occurs through the bidirectional interactions with the robot, such as science reading with the robot in the first case [21] and turn-taking storytelling in the second [5]. The related work demonstrates that social models of the robot perceived by children can benefit their learning experience. This has motivated this thesis to continue investigating the role of social robots, but from a different perspective of children's intrinsic characteristics development based on the learning theory of constructionism.

2.2.3 Social Robots and Creativity

Social robots have been used to help people generate artistic techniques and effects in the creation of Zen rock garden [22]. The research compares a social robots with Power Point presentation that provides the same core information for the creation, but the robot engages with the participant by listening to their ideas and asking questions. The results are measured by the rate in which the participant produces the creative expressions and interviews on participant's perception on their creative process.

Another research designs a weekly play program for children and aims to stimulate verbal creativity, dramatic creativity, graphic-figurative creativity and plastic constructive creativity [23]. The program consists of 75-minute weekly play sessions and lasts for one school year. The performance is measured by Torrance Test of Creative Thinking (TTCT) and Scale of Creative Behavior and Personality Traits (EPC).

Research also finds that using a social robot does not necessarily sparks creativity, where participants collaborate with robot in drawing tasks [24]. Robot and participants take turns in drawing and the creativity score of the drawing is calcu-



Figure 2.5: Rock Garden Design with a Social Robot [22]

lated using Test for Creative Thinking-Drawing Production (TCT-DP). However, there is no statistically significant difference between collaboration with robot and tablet.

The prior work has investigated various scenarios where the social robot serves as a companion or collaborator in the verbal or visual tasks for creativity. However, the mostly commonly used modalities of social robots are speech and gestures in the creating process, while the robot's spacial movement is less adopted. This thesis presents an augmented system where children and the robot's movements and interaction in space are utilized for the creation tasks.

2.3 Art Making

2.3.1 Children's Art Making

Recent research has investigated children's intention in art making from a social-cultural learning perspective [26]. In the user study, intentions for children's art making include storytelling, representing self and experiences, understanding subjects and phenomena, changing moods, playing for experimentation, projecting imagination to reality, building relationships with peers and making gift for important ones. By using art making as a way to connect their inner beings with their social and cultural surroundings, children make meanings in their lives.

Early research has also explored the social knowledge children built through art education [27]. Social knowledge is the meanings structured by a society for interpreting life experiences within it. Social knowledge serves as a commonly available



Figure 2.6: Children's digital paintings [25]

conceptual framework that enables individuals to communicate with one another. From the author, children are provided with meanings that can be used to formulate their own interpretations about the nature of art. The user study shows that higher grade students mention act of art is creating and expressing, while for lower grade is making and doing and art is only a productive endeavor. Also, the content for higher grade is more abstract, such as feelings and ideas, while for lower grade is things and stuff.

The perceived art competence in children is researched and the research finds a decline of interests in art as children are older [28]. Researchers invite students from third, forth and fifth grades for drawing activities, inspect their artworks and evaluate the perceived art competence with interviews. The proved hypotheses include that (1) realism and originality increases with higher grade level, (2) lower level of perceived competence of drawing in higher grade, (3) greater competence is associated with realism and originality. Such decline of self-confidence and interest in art since middle schools could be associated with the change of children's belief that they don't have certain skills to make accomplishments in art.

Also past paper has presented children's motivation about art with goal orientation theory, which distinguishes performance goals and mastery goals [29]. The performance goals are to impress others, while mastery goals focus more on self-improvement and skill development. In art education, students could concern the quality of their work and are reluctant to try challenging art tasks and use good strategies in art. The skill development aligns with the mastery goal, while this grading could potentially decrease task engagement and interests in art. Results from the user study shows that "creating art for meeting the teacher's expectation" tends to meet the requirement, but decreases originality and lead to the belief that

one can improve art ability if one tries. While "master goal" leads to using good strategies and the belief that drawing is enjoyable and important [29]. Younger children are more positive about their accomplishments and optimistic for improvement. Beliefs in their skills in art, the potential to improve, different goals for art behaviors not only affect their art making experience and outcomes at present, but also change their attitudes in art in the long term.

2.3.2 Digital Tools for Art Making

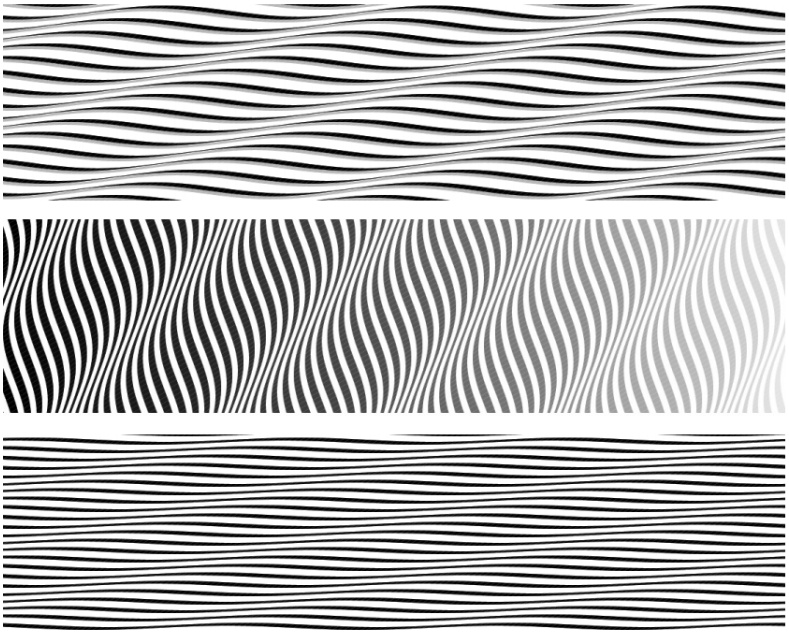


Figure 2.7: Pattern Created using Processing [30]

Past research has explored children's art making with digital tools. One research investigates the effects of digital pen on children's development in symbol and sign formation [25] . In comparison with traditional drawing tools, the paper demonstrates that the digital pen allows children experimenting with color, lines and shapes in faster iterations. Children are able to mix colors and test out color theory, use strategies such horizontal arc, vertical arc and push-pulling to understand symbols and signs. With this tool, children can make exploratory actions on the screen with their own initiatives.

Another recent research investigates digital art making in a classroom setting, where students collectively construct the artwork with a newly introduced digital resources and the teacher provides minimal intervention [31]. The computer with an art making software called Tux Paint is placed in the classroom for one week and students interact with it during the free-flow activity time. One of the findings is that children tend to repeatedly use ideas and imagery in order to reinforce their particular concept of digital art making. They create metaphors to make sense of the digital images they made that may otherwise look like scribbling with traditional art medium. It's also found that children tend to perceive particular peers more

confident in using digital technologies as more competent in digital art making, while perceive some peers less competent or even incompetent. That says, digital art making tool is not only related to children's art-making competency, but also self-confidence in using the digital technology in general. As children may have different exposures and proficiency in technology, it is important to consider their acceptance of new technologies.

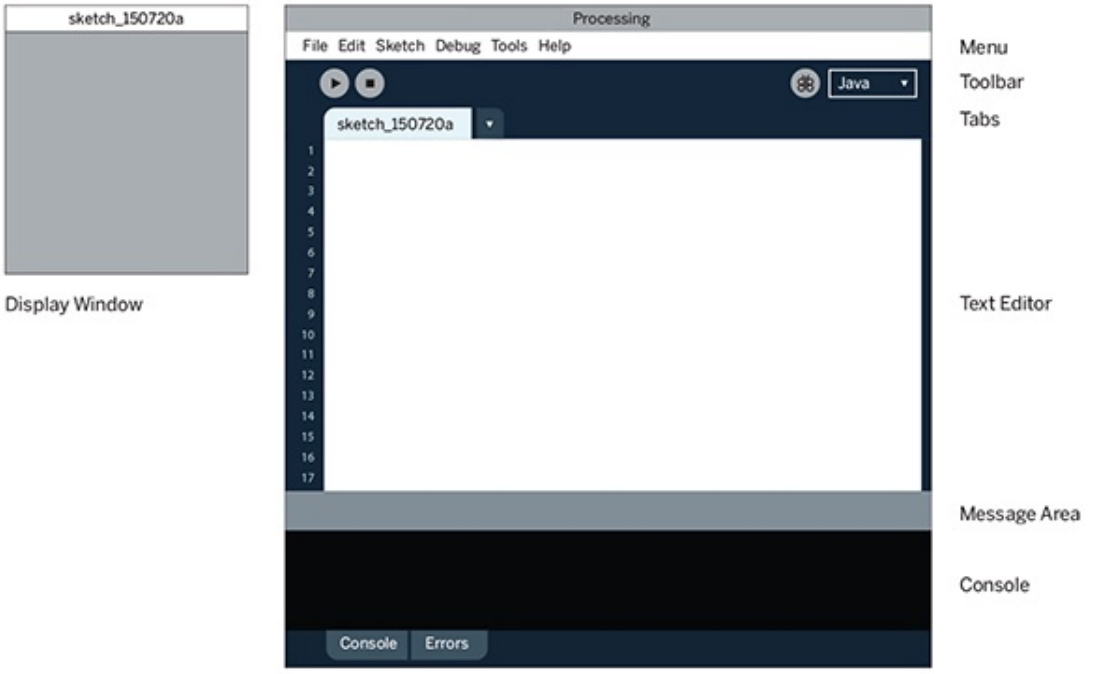


Figure 2.8: Integrated Development Environment for Processing [30]

Invented by Ben Fry and Casey Reas in 2001 [30], Processing provides an IDE, a simplified programming language and libraries for people to write visual code in a fast way. Since its origin, it quickly became a widely used tools in the context of visual arts. Twenty years since its invention, Processing is still widely used by artists, designers, students, and many people without professional programming experiences.

There are a few reasons contributing to its success. First, the software as an art medium has its own qualities in comparison to traditional medium. Computer graphics in the software projects real world scenes, simulates physical laws, processes human behaviors and represents it in the dynamic digital forms. By combining visual messages, sounds and text, the software tool enriched the forms of expressions and communications in the art space. Besides using software as art medium, Processing also provides a simple platform for coding and attracts many less technical users. Its IDE (Integrated Development Environment) is as simple as a sketchbook, reduces the complexity of programming languages and wraps popular APIs and libraries for handy use. Lastly, it inspires people with different professions to think in another way. Engineers may develop their visual sense by making digital arts, while artists and designers can develop the systematic thinking with programming.

This thesis adopts a similar tool called openFrameworks, which is written in

C++. With the same benefits with Processing, openFrameworks provides a simple and clear structure for visual programming. In addition to this, openFramework is chosen because it is compatible with ROS and reduces the complexity of system integration in implementation stage.

Chapter 3

Preliminary User Research

3.1 Observation from Art Teacher Social Groups

Insights into the current practice of K-12 art education are collected from online art teacher forums with more than twenty thousands members. Topics related art education such as ideas for art assignments, classroom management, teaching methods and art learning goals are frequently shared in the group by teachers from all over the world.

Under the question "What do you think is the art educational goal of our current education system?", some teacher wrote "I have recently been working through the idea of building self confidence that art is not 'perfect' and they don't have the worry about something that is not exactly the way they planned it". From a perspective of problem solving, another art teacher wrote: "Development of creative thinkers who can persevere through a problem, consider multiple solutions, revise as needed, and verify to determine if problem was solved". Also, one teacher mentioned building connection with the surrounding world, which echoed Maxine Greene's theory in Aesthetic Education, "It to develop both competences that can be used in many aspects of their lives (imagetic and musical appreciation, body consciousness, sensibility etc) and to contextualize real world problems and history through Art in its many forms".

In discussing children's decline of engagement in art classes, some teacher complained the ignorance of art classes comparing with other major academic subjects. The teacher pointed out that the the demand on learning content is intensified and teachers have to track the progress for the major subjects. "There's no time in the day for them to color, cut and glue. These days it takes an exceptionally dedicated and creative teacher to find time to integrate the arts".

From the online forum observation, many art educators view art making as an important way for children's personal character development such as risk taking, persistence and critical thinking, that are beyond the art skill itself. However, they are also concerned with the fact art is increasingly marginalized in face of other

academic subjects such as mathematics and science in school.

3.2 Observation from STEAM Carnival



Figure 3.1: Robot Design from Children

The user research is conducted during the STEAM Carnival event hosted by Children's Museum of Pittsburgh in November 2019. The first activity aims to understand children's drawing behaviors and perception on robots. Children are asked to design robots with certain functions, such as "Design a robot that creates art with you", "Design a robot that tells stories for you", "Design a robot you want to be friends with".

Differences among children's varying age groups are observed. For example, children between age 8-12 are the most motivated to work on the design task and can complete it with their own thinking, while children under 6 are not quite able to follow the guide and would need parents' assistance in finishing the task. Some children older than 12 tend to think this activity is childish and not willing to participate.

In terms of children's engagement, most children could focus on the drawing task for around five minutes by themselves. Besides demonstrating their design thinking with drawing, children have other different ways for meaning making. Some children write down the design rationale with detailed text descriptions next to the drawing,

while some children like to talk with parents about what they are making as they draw.

The second activity invites children to interact with the robot in groups. One child controls robot movements and has the robot bump into other children. One observation is that the social dynamics among a group of children changes greatly when they chase around the robot. Children tend to treat the robot as one player in the game and get excited by the unexpected actions from the robot.

"I have never seen a robot like this", "What does it do?", most children mentioned that they never played with mobile robot like Kuri (Kuri robot is around 6 feet tall). Though it is common for children to have robot toys or other smart devices at home such as Amazon Alexa, few children have engaged with social robots before. They always get surprised and excited when the robot display expressive behaviors such as nodding and smiling.

3.3 Drawing with Social Robot using Joystick

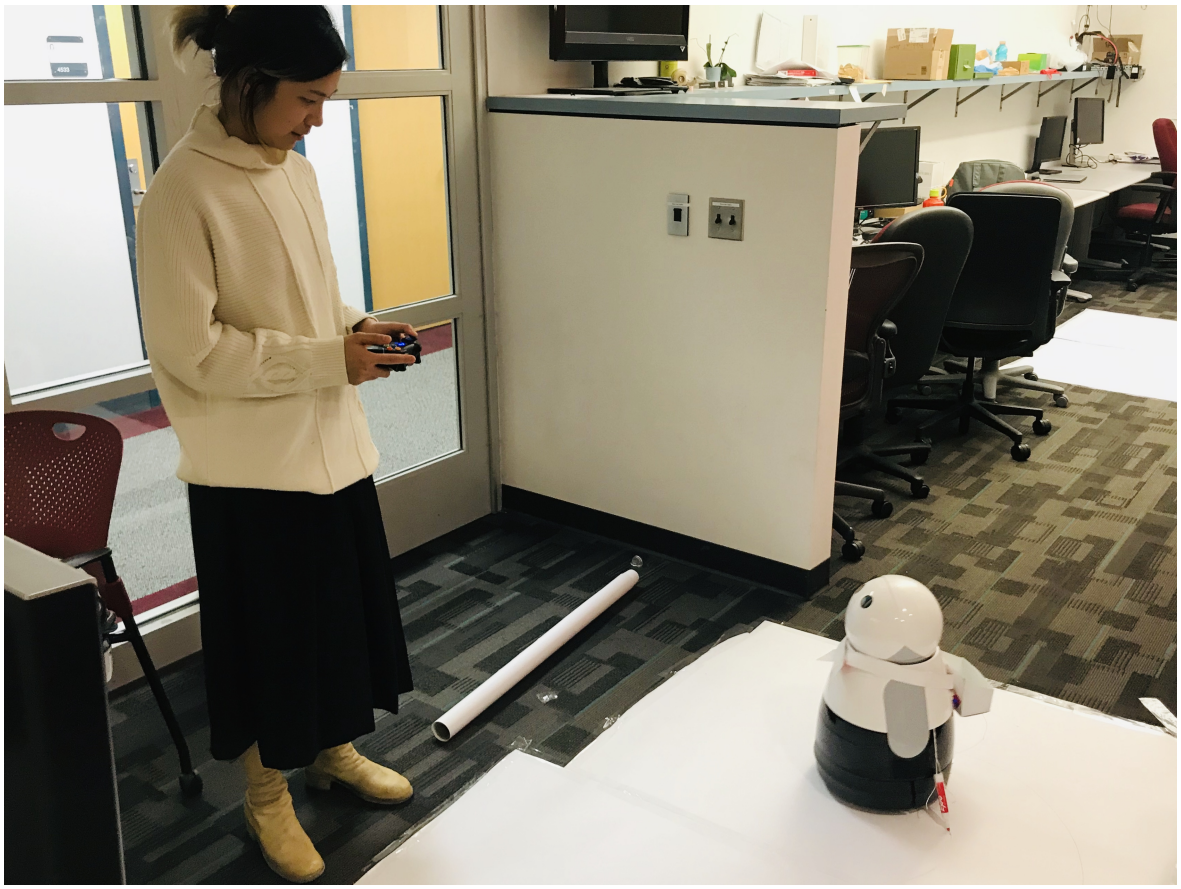


Figure 3.2: A photography of a participant controlling Kuri robot to draw on floor with joystick

This user testing is particularly interested in the expressive social factors on the robot and aims to investigate how it can affect people's decision making in

drawing. The social robot Kuri is programmed into two modes: with or without expressive behaviors. It displays expressive behaviors with gaze, head movement, body rotation, sound and chest light. There are two ways for robot control, one is from the participant's joystick and the other one is from the researcher's remote control on PC. The participant controls the robot movement for drawing with the attached markers, while the researcher triggers the robot's expressive behaviors and movements that are unexpected from the participant.

The experiment is controlled with two conditions: robot with social behaviors and without. The social robot Kuri is programmed into two modes: with or without expressive behaviors. Upon completion of the drawing, the participant is interviewed to answer questions about perception of the robot and its effect on the collaborative drawing. Some answers are as following:



Figure 3.3: Kuri robot's accessory for ground drawing

- Expressive Case: "When the robot showed a happy expression, I tended to use the same pattern again because of affirmations from the robot".
- Expressive Case: "I feel the robot was trying to communicate with me."
- Expressive Case: "I tried to have the robot not go outside of the paper as I feel it didn't want to go out".
- Non-expressive Case: "I tried to have the robot not go outside of the paper as I think it will get the floor dirty".

The results demonstrate that the robot with expressive behaviors has affected participant's decision making during the drawing process. Particularly, the participant intends to attribute agency to the robot in the expressive case and views it more as a partner instead of a tool in the collaborative drawing. This has provided insights into the further design of the interactive system and robot social behaviors.

Chapter 4

Interactive System Design

4.1 Research Question and Goal

Research Question: How would social behaviors of the robot affect children's willingness to explore in art making?

This thesis hypothesizes that social behaviors exhibited by the robot could contribute to more children's exploratory actions for digital art creation. Besides, it's hypothesized that children are more likely to interact with the socially behaved robot again, indicating that they have a higher level of affection towards the robot with social behaviors. In terms of children's perception on the robot, it's hypothesized that children would attribute agency to the robot in the social condition, perceive the robot as a partner more than a tool and view the final work as a collaboration with the robot.

Taken together, the hypotheses are listed as the following:

- H1: Children interacting with the robot with social behaviors will exhibit more explorative behaviors.
- H2: Children are more willing to interact again with the robot with social behaviors than without.
- H3: Children will perceive the robot with social behaviors as a peer more than as a tool.
- H4: Children will perceive the robot without social behaviors as a tool more than as a peer.
- H5: Children will view this final work as a collaborative efforts with robot.

4.2 Introducing Kuri Robot

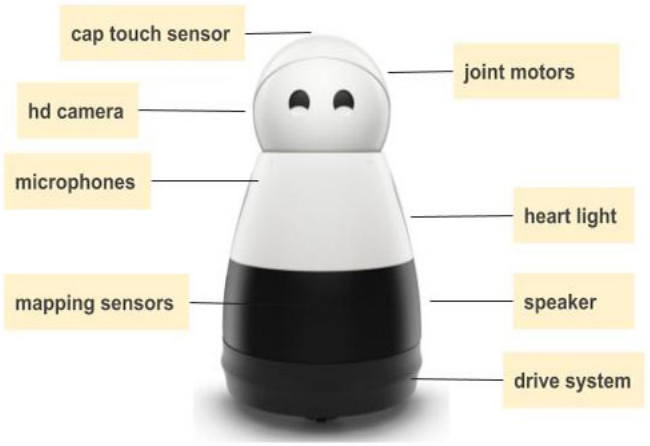


Figure 4.1: Kuri Robot Introduction

Kuri robot is a commercial product designed for home use. It is about 6 inches tall and 3 inches wide. It moves around with two wheels and exhibits social cues by head movement and eyes blinking. It also make sounds with two speakers and show colors with its chest light. There is one camera in one of the eyes and the video feed can be accessed.

This robot is chosen because its children-friendly appearance, expressive social behaviors and capability of navigation. It is also important that the robot opens access to its Linux kernel for customized control over the robot.

4.3 Interaction Design

This section presents two concepts for the interaction design. In the first design, the participant triggers the robot's patterned movements for abstract art making. In the second design, the participant chooses one palette to interact with out of multiple choices where each palette is gamified with its own theme and interaction mode.

4.3.1 Robot Behaviors Overview

In order to investigate the research question "How would social behaviors of a robot influence children's willingness to explore in the digital art making?", there are two robot conditions: robot with social behaviors and without social behaviors.

Here are four types of social behaviors that the robot exhibits to increase its perceived socialness, i.e. Cheerful Look, Lost Look, Curious Look and Pay Attention. Each type of social behaviors is associated with a list of animations that the Kuri robot can play as shown in table 4.1 and figure 4.2. These animations are selected

and categorized from the built-in animation list provided by the robotics company [32].

Social Behavior Type	**Animations**
Cheerful Look	gotit, greeting_2, live_love, tickle
Lost Look	huh2, ponder_sad, no_1, huh1_docked
Curious Look	attention_look_around_2, look_around_adults
Pay attention	photo_shoot_1_docked

Table 4.1: Table for Robot Behaviors

In the social robot condition, robot social behaviors are triggered during the interaction process. The "Cheerful Look" type will be triggered if the kid makes positive progress on the canvas, the "Curious Look" type will be triggered if the kid's engagement level is low, and the "Lost Look" type will be triggered if the kid blocks the robot path. When triggering each type of social behaviors, one animation of this type is randomly selected from its group to increase the uncertainty of robot behaviors. Besides, there are at least ten-second time gap to trigger social behaviors in order make the robot behave in a more natural way.

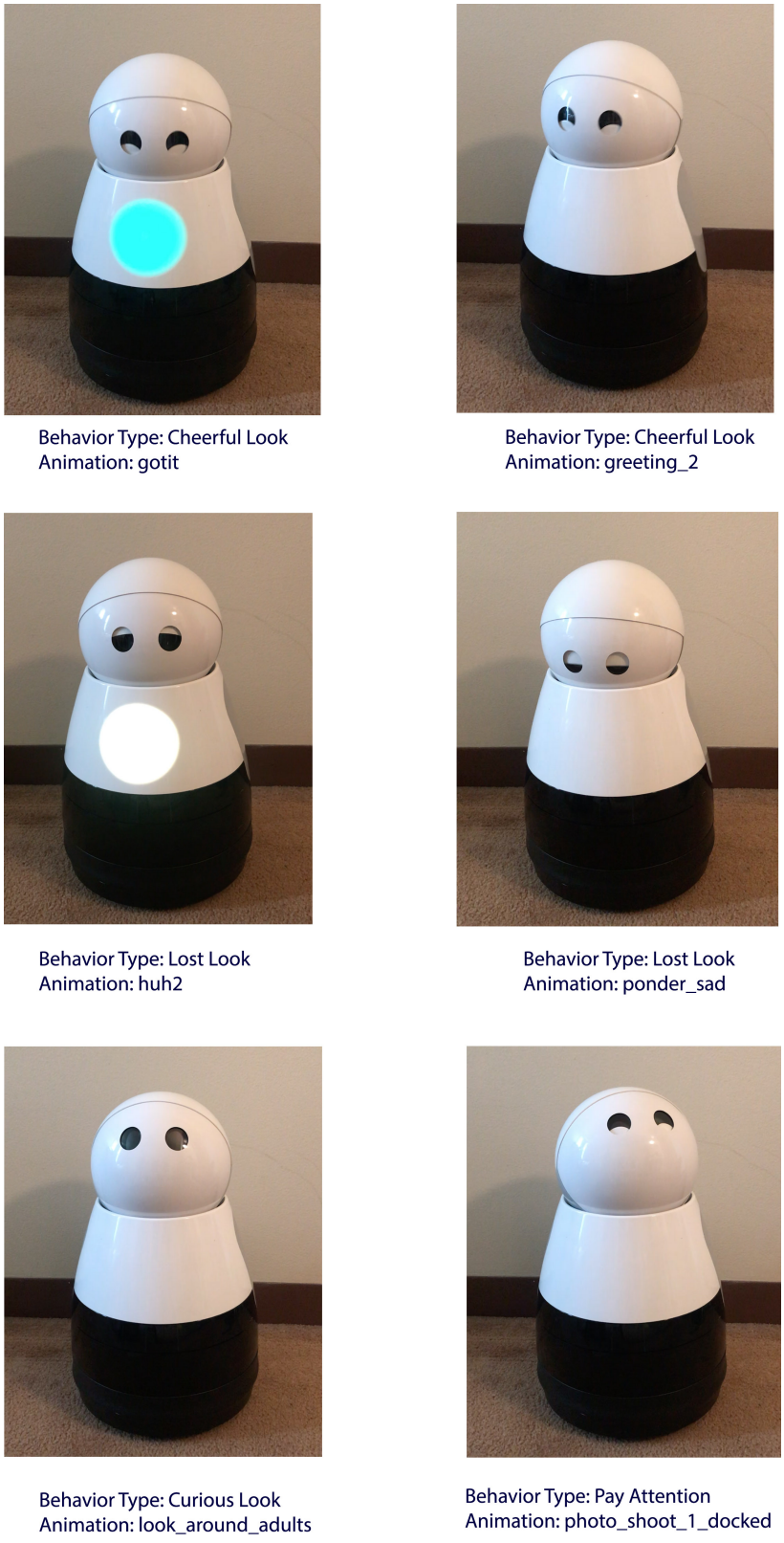


Figure 4.2: Social Behavior Types and Animations

4.3.2 Design I: Drawing Patterns with Robot Motion

Design Concept

"An active line on a walk, moving freely, without goal. A walk for a walk's sake. The mobility agent, is a point, shifting its position forward" [33], Paul Klee derives the formation of shape from movements with a focus on the kinetic-mobile features in his book *Pedagogical Sketchbook*.



Figure 4.3: Line on a walk by Paul Klee [33]

Inspired by Paul Klee's theory, the current interaction design considers the mobile robot's movements including both linear and angular speeds and creates different geometries by controlling the robot's speed at a certain time. In addition, drawing time as another factor is considered in the shape formation by robot, that the stroke is thicker in the beginning and gets thinner gradually until the completion of the drawing as shown in figure 4.5. Children trigger different movement patterns of the robot by stepping the icon on the projected floor or petting the robot head. The pattern icons projected on the canvas demonstrate which type of movements is to be triggered, while touching the robot head triggers the movement pattern randomly that is unknown to the participant ahead of time. Children can choose to just trigger one pattern and wait for the robot to finish it or create new shapes with combination, that is to trigger a new pattern before the robot finishes the current one.

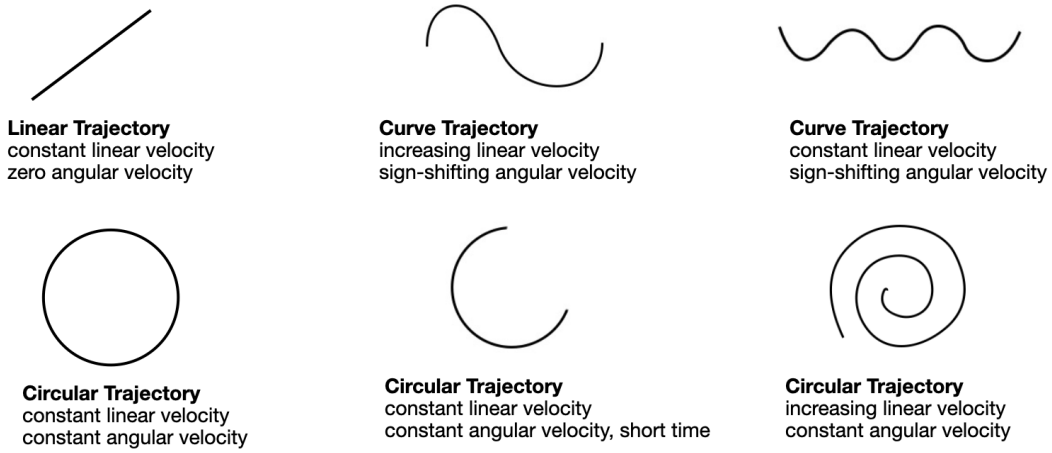
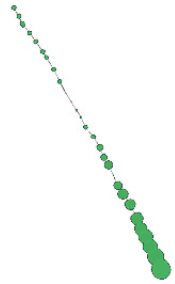
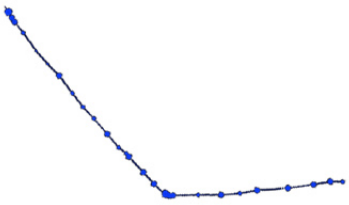


Figure 4.4: Pattern Generation Rules



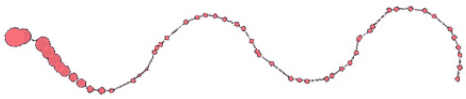
Time: 0 - 5s
Angular Velocity = 0
Linear Velocity = 0.1 m/s



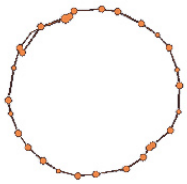
Time: 0 - 2s
Angular largeVelocity = 0
Linear Velocity = 0.2 m/s

Time: 2 - 3s
Angular Velocity = 1 r/s
Linear Velocity = 0

Time:: 3 -5s
Angular Velocity = 0
Linear Velocity = 0.2 m/s



Linear Velocity = 0.1 m/s
Alternate angular velocity
between 1.5 r/s and -1.5 r/s
every 2s.



Time: 0 - 5s
Angular Velocity = 2 r/s
Linear Velocity = 0.2 m/s



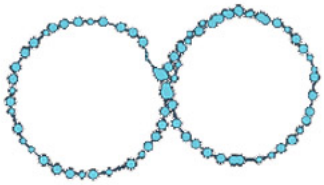
Time: 0 - 4s
Angular largeVelocity = 1 r/s
Linear Velocity = 0.1 m/s

Time: 4 - 8s
Angular Velocity = -1 r/s
Linear Velocity = 0.1 m/s



Time: 0 - 2.5s
Angular Velocity = 2 r/s
Linear Velocity = 0.2 m/s

Figure 4.5: Patterns generated by the robot. They are triggered by stepping on the pattern on the projecting canvas.



Time: 0 - 7s
Angular Velocity = 1.5 r/s
Linear Velocity = 0.1 m/s

Time: 7 - 14s
Angular Velocity = -1.5 r/s
Linear Velocity = 0.1 m/s



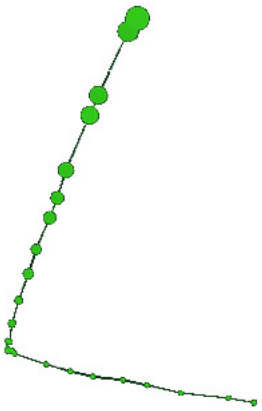
Time: 0 - 1s
Angular Velocity = 0
Linear Velocity = 0.2 m/s

Time: 1 - 3s
Angular Velocity = 1.5 r/s
Linear Velocity = 0

Time: 3 - 4s
Angular Velocity = 0
Linear Velocity = 0.2 m/s

Time: 4 - 6s
Angular Velocity = -1.5 r/s
Lienar Velocity = 0

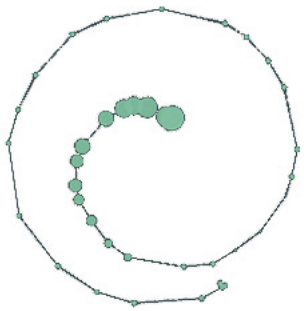
Time: 6 - 8s
Angular Velocity = 0
Linear Velocity = 0.2 m/s



Time: 0 - 2s
Angular largeVelocity = 0
Linear Velocity = 0.2 m/s

Time: 2 - 4s
Angular Velocity = 1 r/s
Linear Velocity = 0

Time:: 4 -6s
Angular Velocity = 0
Linear Velocity = 0.2 m/s



Angular Velocity = 2 r/s
Linear velocity starts from
0.1 m/s and increases by
0.005 m/s every 0.1s

Figure 4.6: Patterns generated by the robot. They are triggered by petting the robot and the participant doesn't know which pattern is to be triggered.

Interaction Space Setup

The interaction space has a Kuri robot and a projection area from a top down projector. In order to create new patterns, children either interact with shapes on the floor or touch the robot head.

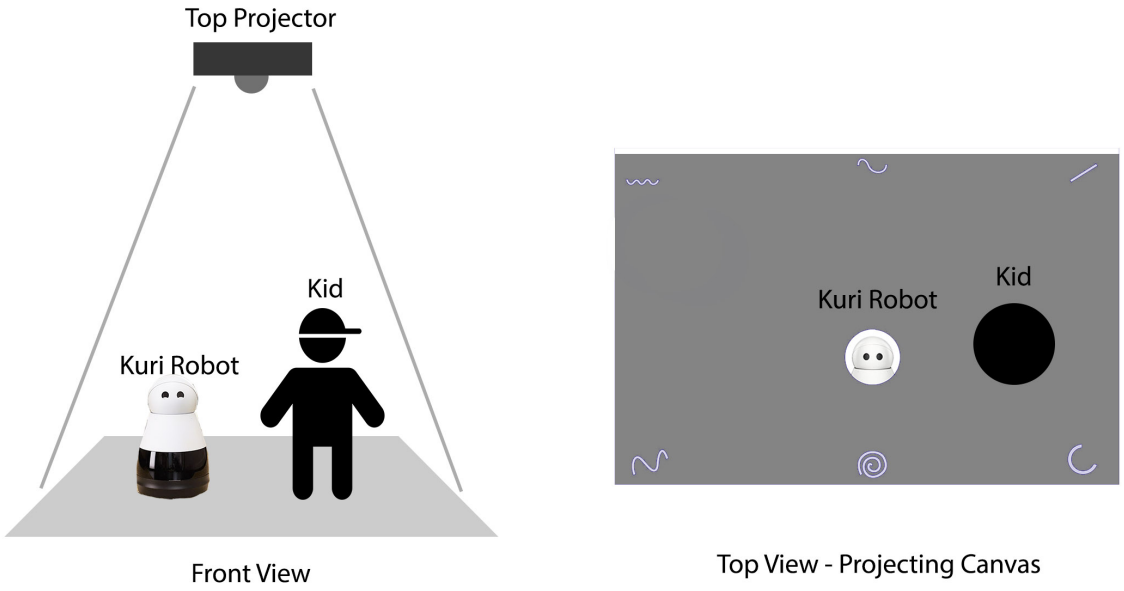


Figure 4.7: Interaction Space Setup

Interaction Process and Prototype

Interaction mode 1. Each pattern drawing from the robot is triggered by stepping on the pattern icon. 2. Hidden drawing patterns can be triggered by petting the robot head. 3. The newly generated pattern will float on the canvas until the kid fixes it on the canvas by stepping on top of the pattern. 4. If the kid blocks the robot path or the drawing time is up, the robot returns to the idle state and one drawing is complete. 5. If a new pattern is triggered before the previous one is finished, the new pattern is combined into the previous one.
Robot behaviors under social condition 1. Robot exhibits cheerful behaviors as a new pattern is selected. 2. Robot exhibits curious look if the kid doesn't trigger any pattern for a while. 3. Robot exhibits lost behaviors if the kid blocks its path.
Expected explorative behaviors from participants 1. Try out different pattern combinations 2. Touch robot head and explore the unexpected patterns

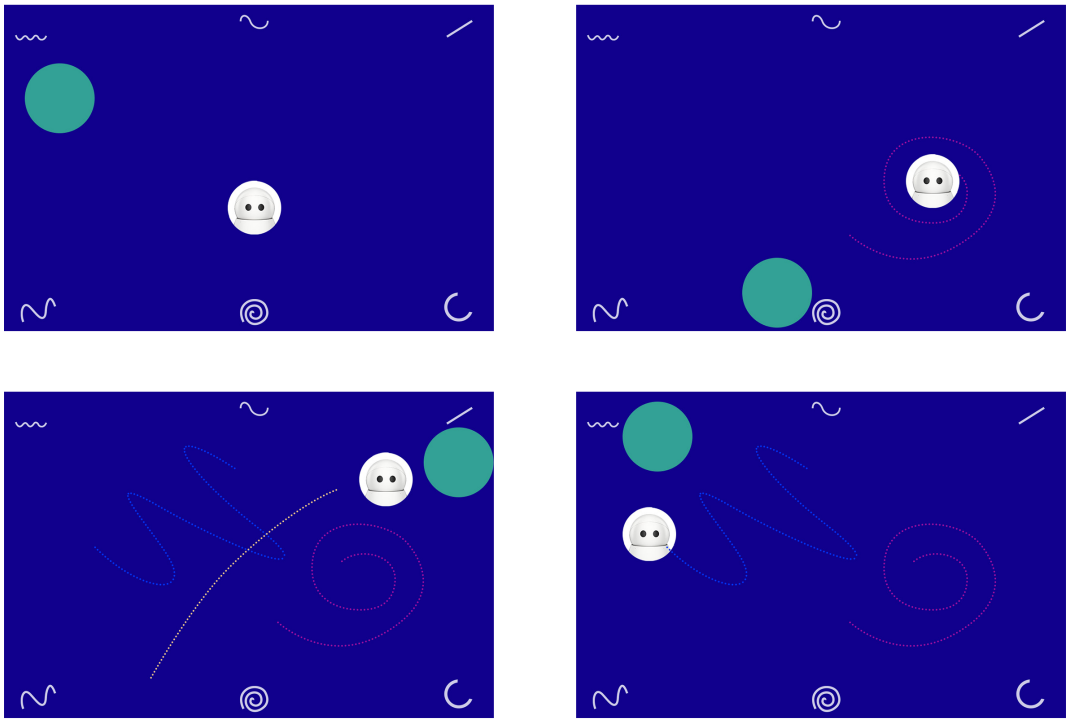


Figure 4.8: Interaction Process Concept

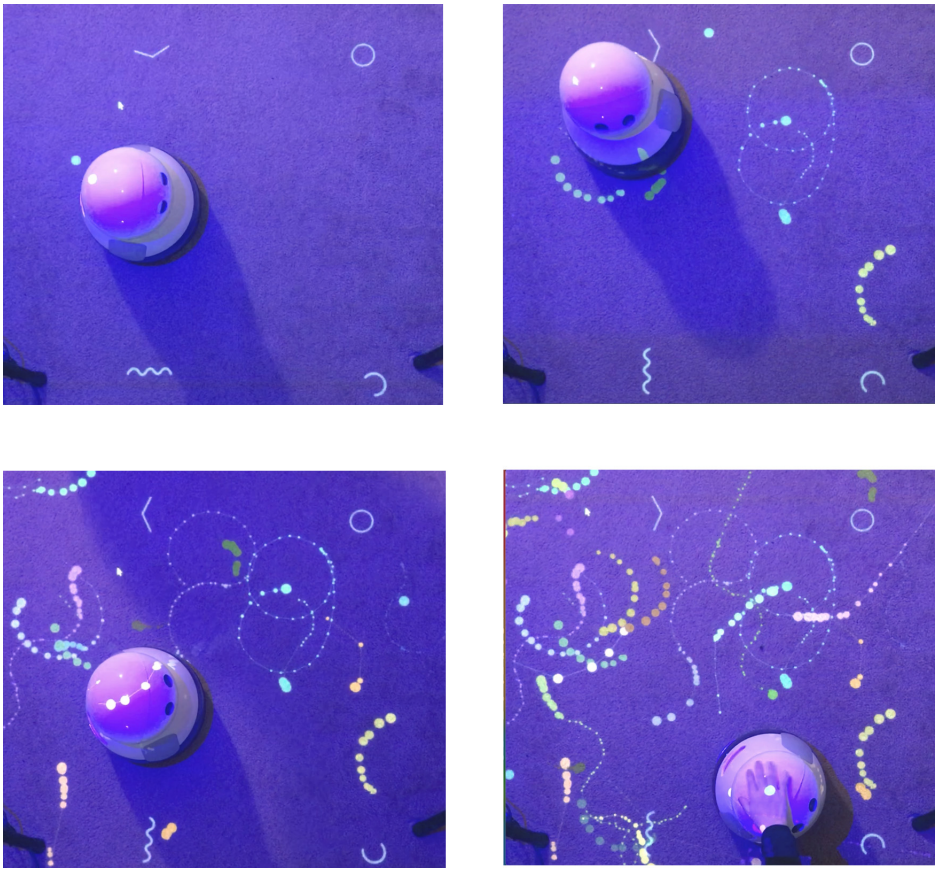


Figure 4.9: Interaction Process - Top View



Figure 4.10: Interaction Process - Front View

Robot Social Behaviors Design

In the social condition, the robot displays cheerful behaviors when a new pattern is triggered. The lost behaviors are triggered if the robot path is blocked. The curious behaviors are triggered if the participant doesn't interact with the canvas or robot for a while. However, the robot would appear to be strange if it plays social behaviors too frequently, so the current system requires a minimum 10-second time gap between triggering two social behaviors. The robot animations corresponding to its social behaviors are described in table 4.1.

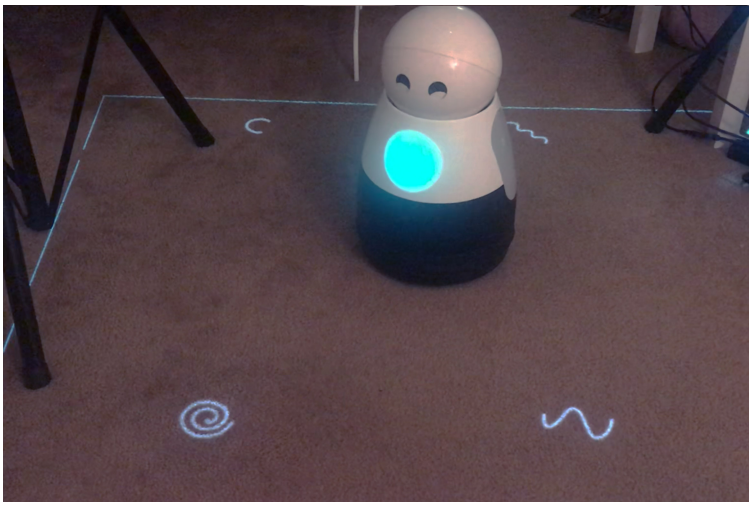


Figure 4.11: Kuri robot displays a cheerful look when a new pattern is triggered.



Figure 4.12: Kuri robot displays a lost look when its path is blocked.

Drawing Process Demonstration

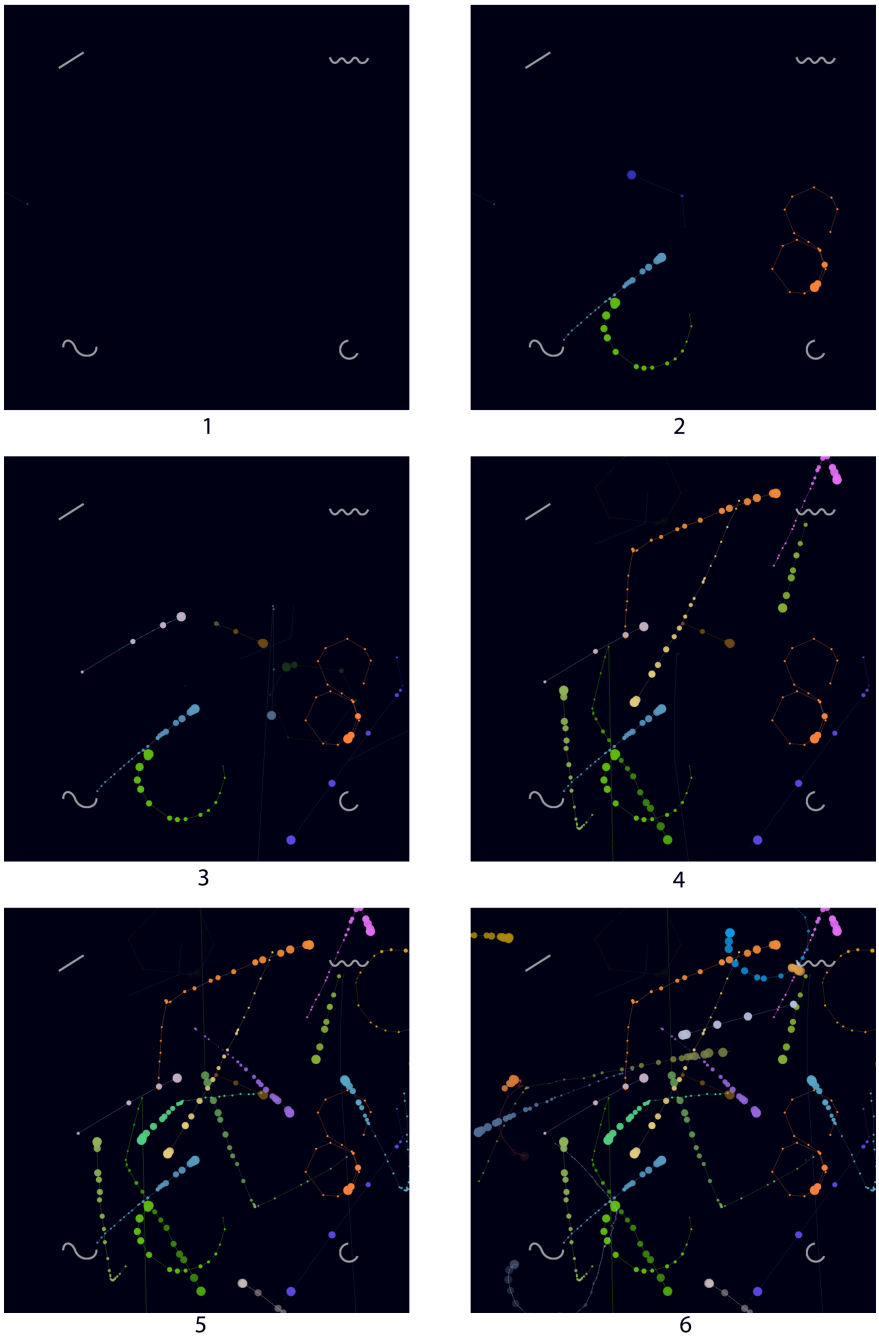


Figure 4.13: Drawing Process 1

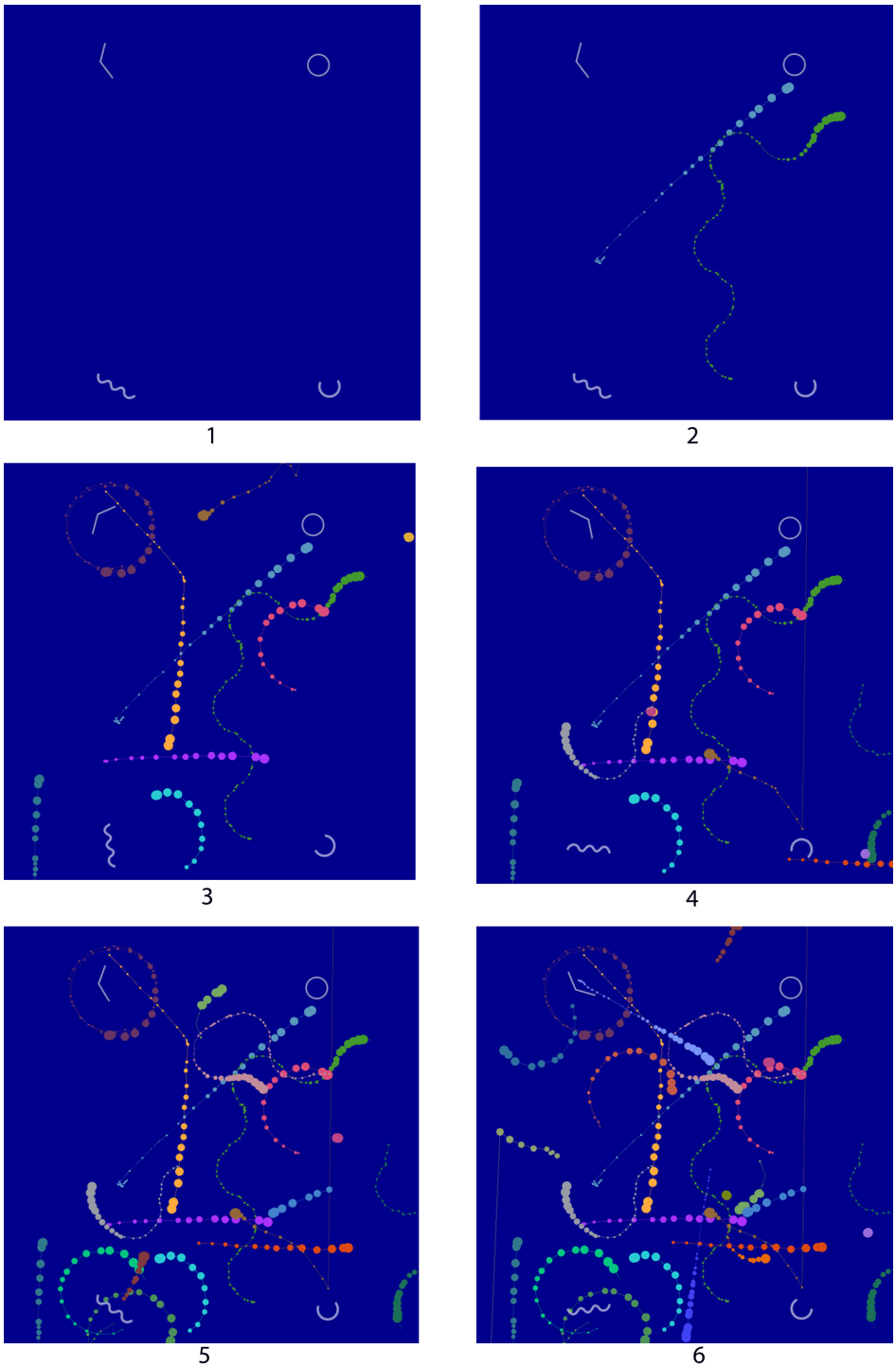


Figure 4.14: Drawing Process 2

4.3.3 Design II: Multiple Palettes Selection

Design Concept

This design gamifies the interaction process and engages children in discovering the hidden rules for animation and robot behaviors. Besides the Kuri robot and the top down projector, the space has a table with hats in different shapes and colors. By picking a hat and wearing it, participants start a new round of interaction with the robot. Each hat corresponds to a palette mode in the projection area. Every palette has its own set of rules to trigger the dynamic computer graphics in the projection. Besides, robot behaviors and the interaction mode changes for each palette.

Between the transition from one interaction round to another, the robot in the social condition communicates with the participant using its gaze, posture, sound and light. If the participant picks a new hat, the robot will display a cheerful look.

In different palettes, robot behaviors in the social condition are dependent on the interaction design of the palette as each of them has a different theme and interaction mode. Two palette designs are demonstrated in the following section and the rest are attached in the appendix.

Interaction Space Setup

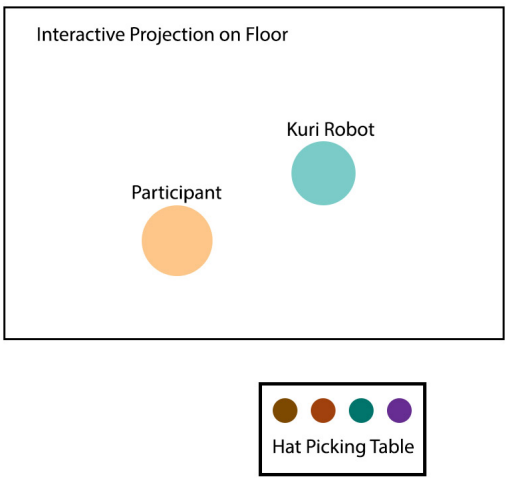


Figure 4.15: Interaction Space Setup - Top View

Interaction Process

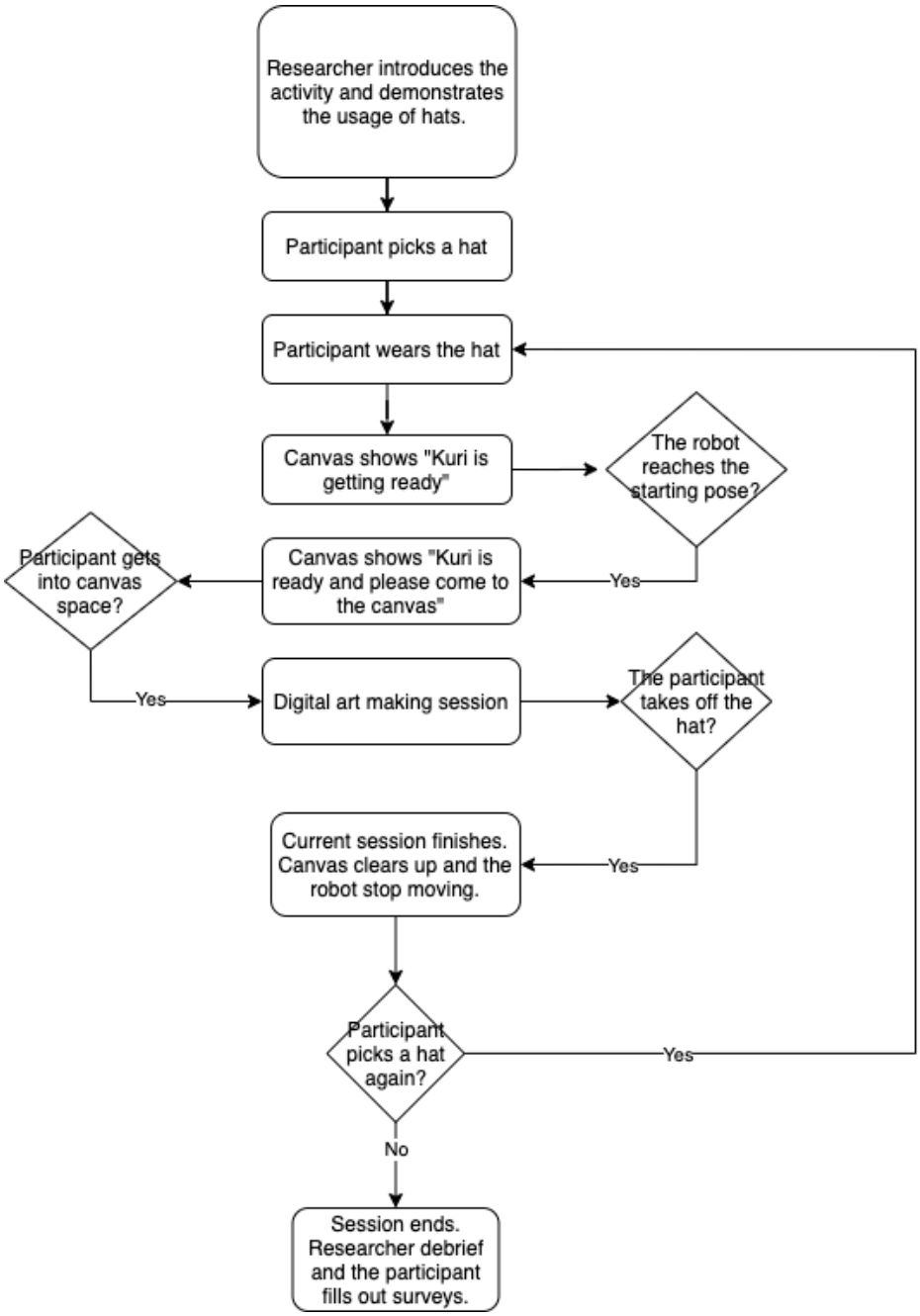


Figure 4.16: Interaction Flow Chart

Designing Interactive Palettes

Palette I

Palette theme and robot behaviors The canvas has a garden theme and the robot moves around circles where plants grow.
Interaction mode 1. The closer participant chases the robot, the more plants will grow in the robot's circle. 2. Flower patterns change as the participant touches robot head. 3. If the participant gets in the way of robot, it moves to another. Otherwise, the robot moves around one circle for one minute and moves to the next one.
Robot behaviors under social condition 1. Robot exhibits cheerful behaviors as it is moving in circles. 2. Robot looks around as it moves from one circle to another one.
Expected explorative behaviors from participants 1. Move around and find out how patterns grow in robot's circles 2. Touch robot head and see what happens

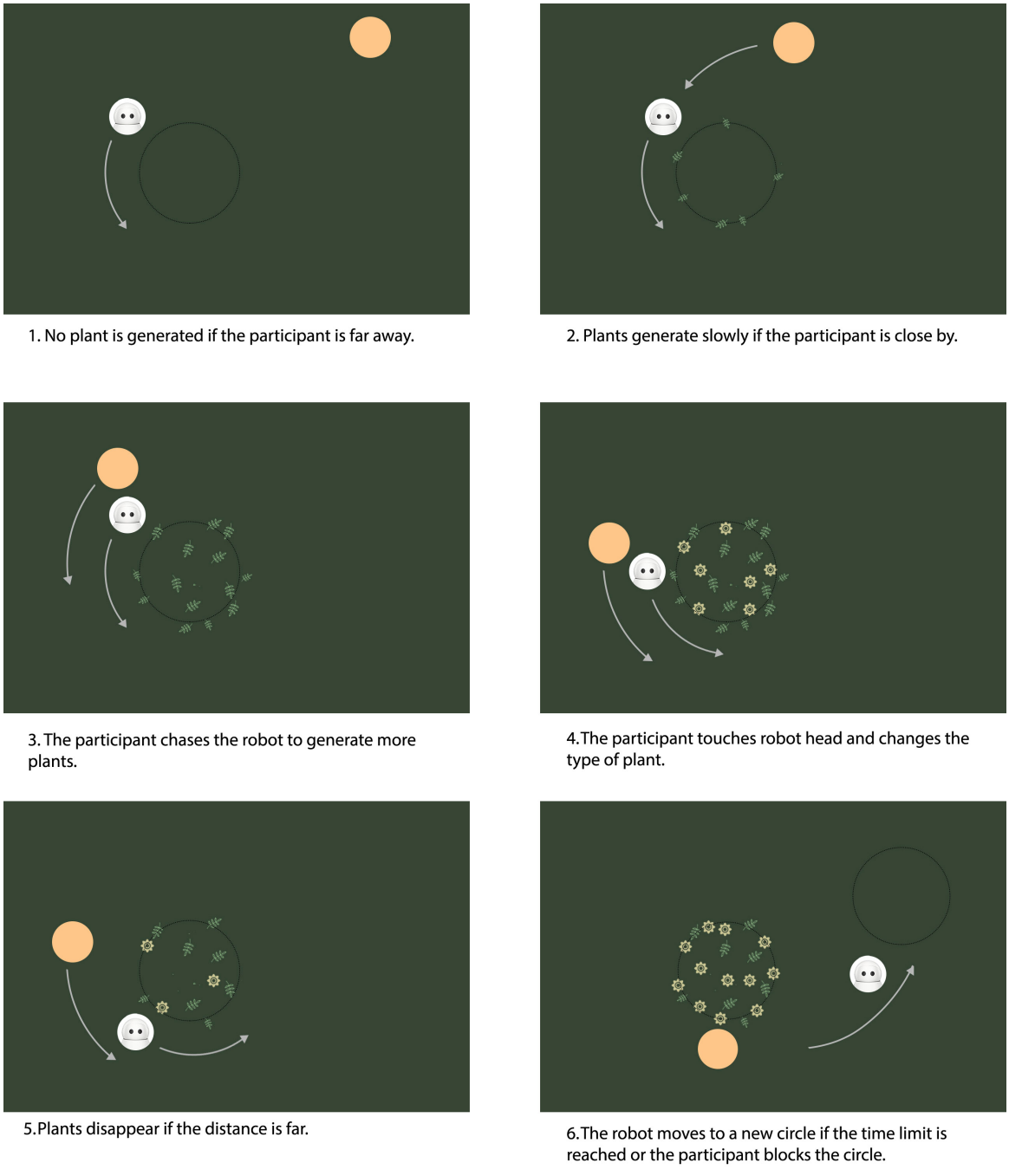
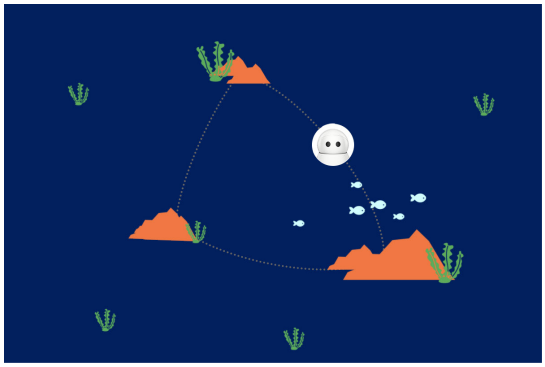


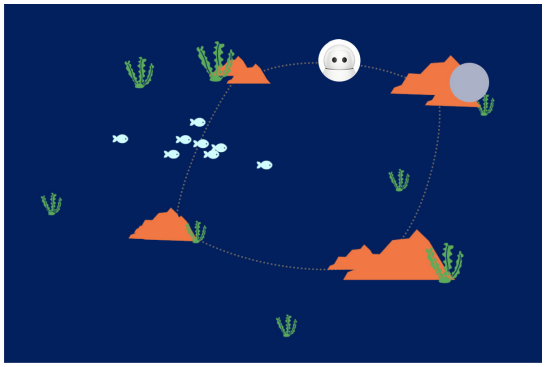
Figure 4.17: Interaction Design for Palette I

Palette II

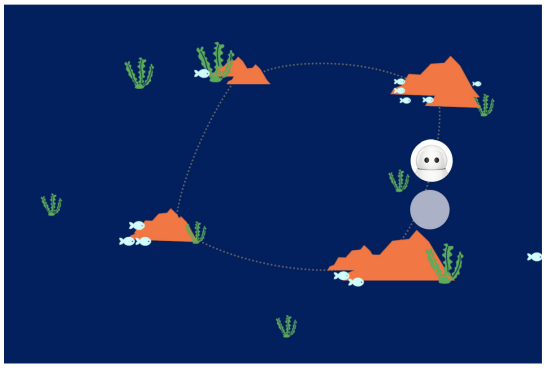
Palette theme and robot behaviors The canvas has an ocean theme with moving fishes, stones and algae. Robot moves from rock to rock and generates swimming fishes from its base.
Interaction mode 1. If the participant blocks robot path, the robot will stop and the moving fish will increase swimming speed to hide in rocks and edges. 2. If the participant steps on a piece of algae, the algae becomes a stone and adds to robot's waypoint. 3. If the participant gets closer to the robot from its side, robot moves faster. 4. If the participant cross fishes created by the robot, the fish changes direction.
Robot behaviors under social condition 1. Robot looks around as it moves. 2. Robot cheers when the participant adds a waypoint.
Expected explorative behaviors from participants 1. Block the robot path and see what happens 2. Figure out that stepping on reef sets new waypoints for robot 3. Figure out that stepping on fish changes their moving direction



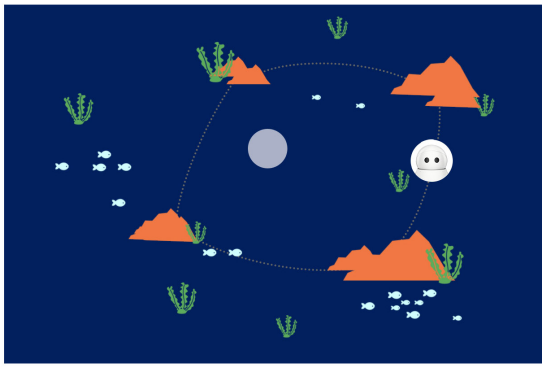
1.Robot moves among rocks.



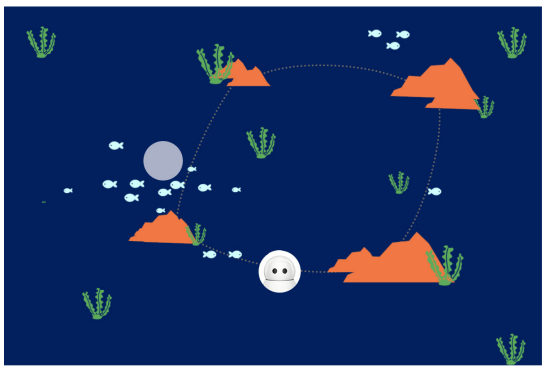
2.The participant steps on algae and adds a new way-point for robot.



3.The participant blocks robot path and stops the robot. Fishes swim to rocks and canvas edge.



4.Robot continues the movement if the participant un-blocks the path.



5.Fishes change moving direction if the participant cross on them.

Figure 4.18: Interaction Design for Palette III

Chapter 5

Interactive System Implementation

5.1 Overall System Overview

5.1.1 Installation and Setup

The system includes the Kuri robot, a projector, a Kinect V2 and a 9 feet x 10 feet supporting stand. The projecting space is 7.5 feet x 5 feet on the floor.

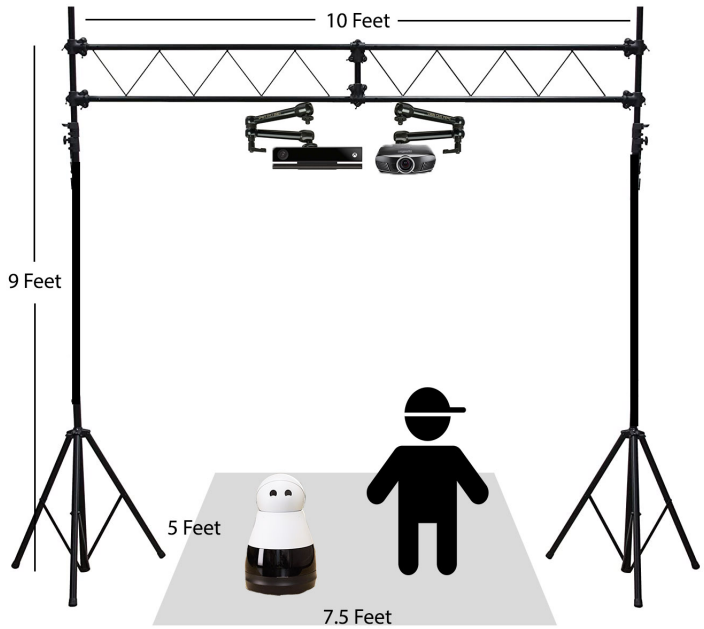


Figure 5.1: Overall installation

5.1.2 Software System

The interactive system consists of three major parts: human and robot tracking, robotics control and interactive computer graphics. The tracking information is sent to controller module and computer graphics module through ros messages. Special attentions need to be paid to compile the system as ROS has its own compilation pipeline (catkin_make), but it can't be directly used for openFrameworks. To solve this issue, config.make file needs to be edited in openFrameworks as the following in order to link to ROS.

```
PROJECT_LDFLAGS+=$(SUBLIBS) $(subst -l:,,$(ros_libs))
ros_libs = $(shell pkg-config --libs roscpp)
PROJECT_OPTIMIZATION_CFLAGS_DEBUG = `pkg-config --cflags roscpp` -w -O2
PROJECT_OPTIMIZATION_CFLAGS_RELEASE = `pkg-config --cflags roscpp` -w -O2
```

The overall architecture for the robotic system design is shown in figure 5.2, that includes three major software components and the communication protocol. As shown in figure 5.3, there are two main types of robot states. Robot movements in patterns are controlled by pre-scripted commands and robot navigation is controlled by the perception-control-action loop.

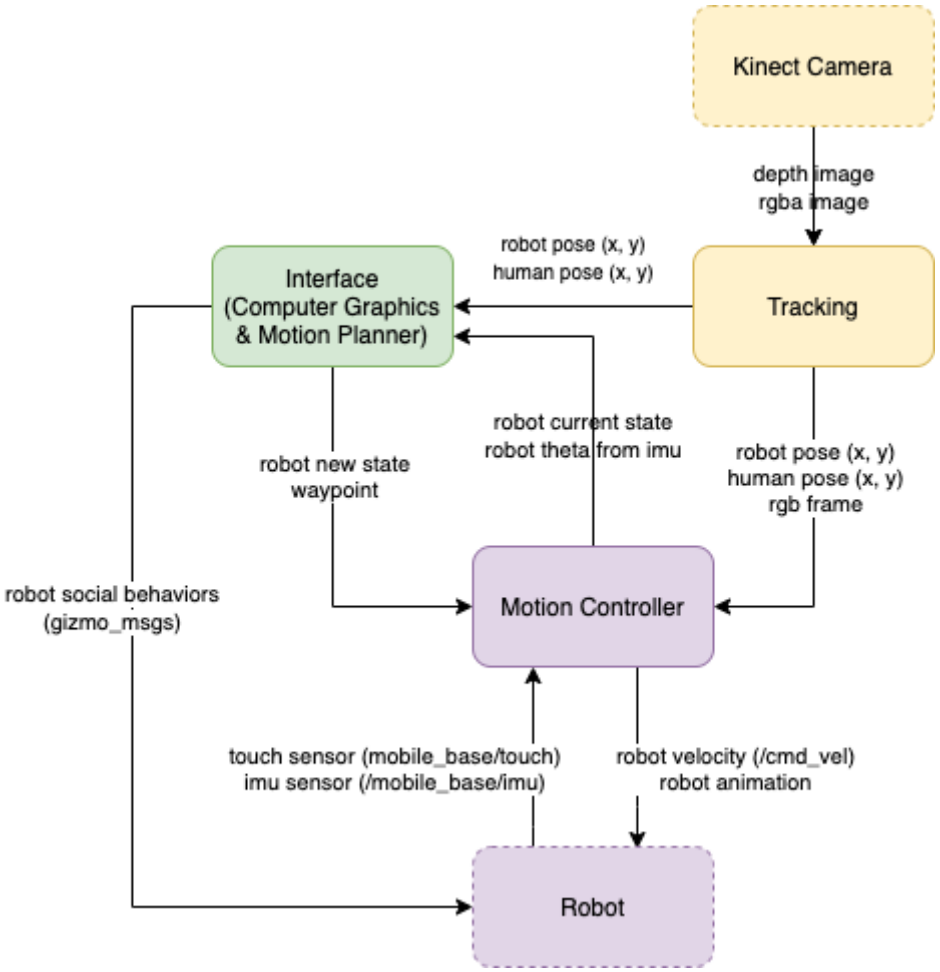


Figure 5.2: Interactive System Design

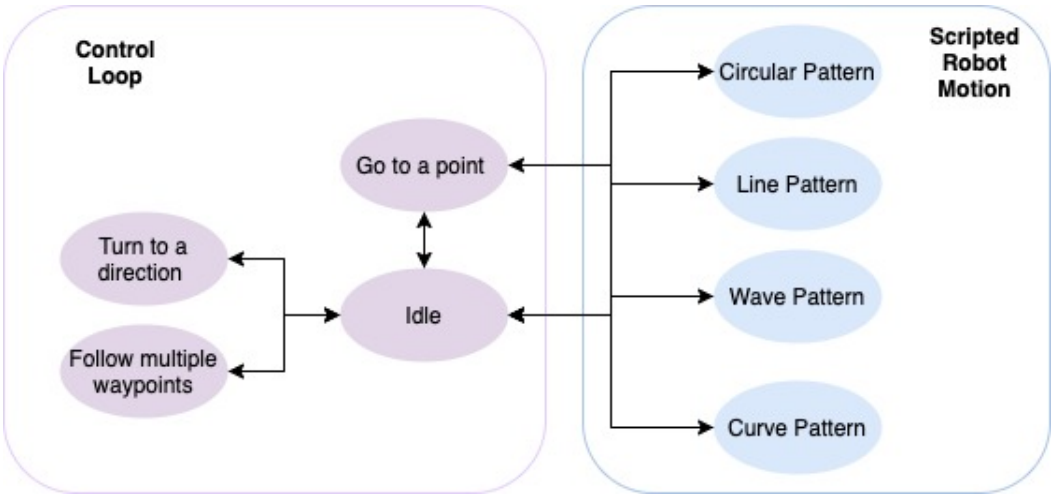


Figure 5.3: Robot States

5.2 Tracking System

Frame of Reference

There are three frames of reference in the system, namely the depth image, RGBA image and the projection canvas. Transformations among the three systems are calculated in order to find the corresponding pose of human and robot in each frame. To keep the readability and consistency of transformation, the frame of RGBA image is used as the world frame for tracking and robotics control in ROS.

Tracking Position with Depth Information

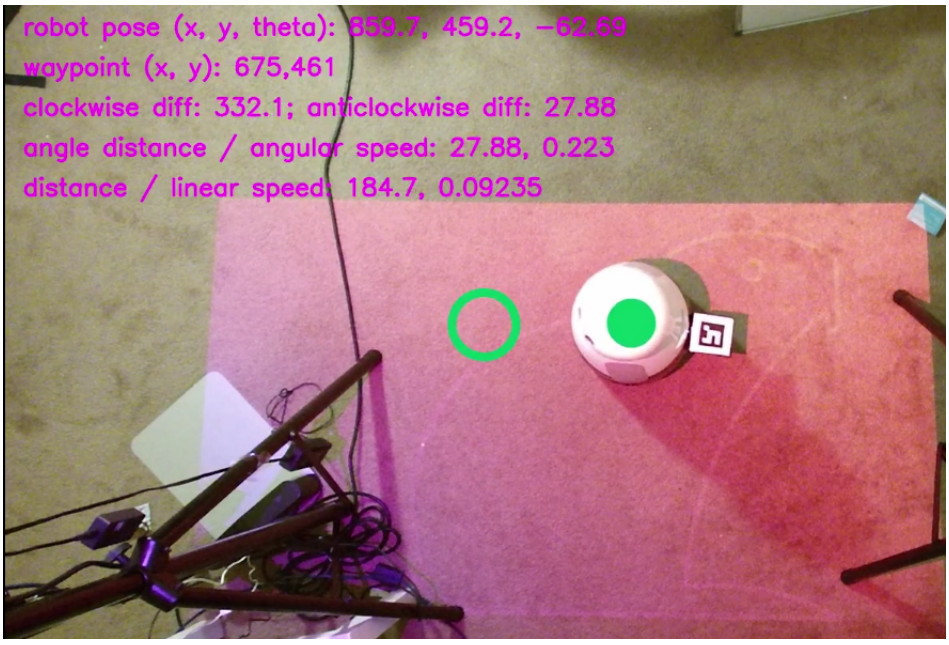


Figure 5.4: Robot Tracking and Control View

Algorithm 1 Robot and Human Tracking

```
1: procedure PROCESS_KINECT()
2:     Initialize kinect_listener
3:     Initialize robot_pose_publisher
4:     Initialize human_pose_publisher
5:     while kinect_listener ≠ empty do
6:         apply registration on rgba_frame and depth_frame
7:         obtain robot_depth_frame          ▷ denoise depth for robot tracking
8:         obtain human_depth_frame          ▷ denoise depth for human tracking
9:         robo_pose = blob_detect(robot_depth_frame)
10:        human_pose = kmeans(human_depth_frame)
11:        aruco_marker_pose = aruco_detect(rgba_frame)
12:        publish robot_pose
13:        publish human_pose
```

Kinect V2 is used as camera to capture depth map and RGBA image for tracking. Kinect sensor is composed of two cameras. The infrared camera has resolution 512 x 424 pixels and can detects from depth range 0.5 meters to 4.5 meters [34]. The RGB camera has full HD color with resolution 1920 x 1080 pixels. Due to the resolution difference between IR and RGB cameras, registration and calibration of the two cameras are necessary. Running on the Linux system, frames from Kinect V2 are extrapolated with libfreenect2 API and get converted to common image format JPEG with OpenCV in C++.

The pipeline for tracking is demonstrated in Algorithm 1. Image processing in Kinect V2 consists of listener, registration, format conversion, tracking algorithms. Listener from libfreenect2 API waits for RGBA image and depth greyscale image when they are available and streams them into the libfreenect::Frame container. The frame rate is around 30 per seconds. Registration between RGB and depth information is conducted with libfreenect2::Registration class. It outputs a color image for depth image and an undistorted depth map. By saying undistortion, this class uses factory parameters for calibration before registration. However, this may cause discrepancy as it is not customized for this particular camera. For the current implementation, an additional calibration with checkerboard is conducted to calibrate RGBA images, but for depth images, factory parameters are adopted right now and to incorporate manual calibration for depth information is an potential improvement for a more robust system.

For the tracking, two different algorithms are adopted for human position and robot position. The pipeline is consisted of data conversion, background removing, detection and tracking. Depth frames from libfreenect2 are converted to CV_32FC1 datatype in OpenCV, which stands for 32-bit floating number with one channel. This ensures that this data type is able to store large depth values. In comparison, RGBA image is converted to CV_8UC4 with 8-bit integer number and 4 channels, which indicates that it has channels R, G, B, Alpha and the range is 0-255 for each channel. Due to the height difference between human and robot, masks are applied to the depth greyscale image in order to extrapolate region of interests by removing noises from background and foreground. Mask with depth range 1700 - 1850 is

applied for robot grayscale image and depth range 0 - 1000 is applied for human grayscale image.

For robot position tracking, the blob detection algorithm is used to track its location as the robot's head has a circular shape in the depth image. The parameters are set as following: minCircularity(0.7), minConvexity(0.9) and minArea(1000), minInertiaRatio(0.7). For human position tracking, the depth map has less noise and Kmeans algorithm from OpenCV is adopted. Given number of clusters in the 2D datasets, Kmeans algorithm find cluster centers for all points with the least mean, in this tracking scenario, that is to minimize the average Euclidean distance between points and the center point in the cluster they belong to. In this implementation, points in the region of interests are added into a list before feeding into the Kmeans algorithm for center point calculation. In order to speed up the image processing speed, every 8 pixels in both horizontal and vertical directions are sampled.

Tracking with Aruco Marker

Aruco marker has been commonly used in augmented reality and robot localization. It is a dictionary of square markers with black and white bits. The matrix maximize the inter-bit distances and enables fast and accurate detection of markers in an image. Each square marker has an identifier and locates its attached point with six-degree of pose information in rotation (quaternion) and translation vectors.

An ArUco marker is a synthetic square marker composed by a wide black border and an inner binary matrix which determines its identifier (id). The black border facilitates its fast detection in the image and the binary codification allows its identification and the application of error detection and correction techniques. The marker size determines the size of the internal matrix. For instance a marker size of 4x4 is composed by 16 bits.

In the early phase of tracking implementation, Aruco Marker is attached at the back of Kuri robot for detection of position (x, y) and rotation theta. A single 4x4 marker with 2 inch edges is used for detection. Before the detection and pose estimation, calibration for Kinect RGB camera is conducted with checkerboard and OpenCV's calibration library. The Camera parameters with a 1x9 camera_matrix and 1x5 distortion_coefficients are obtained upon the success of calibration. These parameters are used for RGB image distortion correction.

However, Aruco Marker detection is not stable under projection as its edge and details become obscure whent the dynamic lighting is projected onto its surface. In addition, occlusion could occur as it is attached at the lower part of the robot body. If the robot rotates around, the marker may not be seen by the camera. Therefore, additional measurements are needed for higher accuracy of orientation tracking in the dim lighting condition.

Tracking Orientation with IMU sensor

As discussed in the Kuri robot introduction, there is an IMU sensor (Inertial Measurement Unit) inside the robot that senses velocity change and robot orientation. Information of the IMU sensor is published by the built-in robotics system over ROS and is of type sensor_msgs::Imu, which contains information of robot orientation, angular velocity and linear acceleration. Besides the topic "/mobile_base/imu", another topic "/client_interface/robot_pose" also contains robot pose information. Upon comparing the orientation result from the two topics with the benchmark result from Aruco Marker in a good lighting condition, the ROS message from topic "/client_interface/robot_pose" has higher discrepancy from the benchmark, therefore is dropped. The ROS message from the topic "/mobile_base/imu" is closer to Aruco Marker estimation and is adopted for the orientation tracking.

Denoising Techniques

Gaussian blur is applied to the depth image before the blob detection and kmeans algorithm. This reduces details in the depth map and leaves out the most important information. In addition, Kalman Filter is applied to increase the stability of the tracking results due to uncertainties in IMU and Kinect sensor measurements. Kalman Filter combines the last state with the current sensor measurement, with the goal to minimize the discrepancy between the current estimation and measurement. For instance, if the current detected position has a large deviation from the previous result, Kalman Filter would smooth out the sudden change.

In the current implementation, multiple 1D Kalman Filters are applied to position tracking and orientation individually. However, a more robust approach would be applying one 2D Kalman Fitler for the pose estimation as a whole and this would be a future improvement for the system. In addition, only IMU measurement is adopted for orientation tracking, but it is possible to combine tracking results from both Aruco Marker and IMU sensor and improve the overall accuracy.

5.3 Robotics System

Robot Control Overall

The robot system is developed with ROS (Robotic Operating System) in C++. On a higher level of robot control, ROS scripts can be used to trigger built-in animations and control movements through the Linux kernel on the robot. The remote controlling system is built on a Linux PC that the command can be sent to the robot wirelessly. In addition, the controller is implemented on a joystick for easier operation.

Robot Navigation Control

There are two modes of robot navigation control. The first mode is that the user controls the robot's linear and angular velocity with joystick or keyboards. The second mode is that the robot navigates to waypoints autonomously with perception and PID control (Proportional–Integral–Derivative).

Checklist for configuring remote communication in ROS
Kuri robot terminal: `sudo iptables -F`
PC terminal: `export ROS_IP = PC_ip_address`
PC terminal: `export ROS_MASTER_URL = kuri_ip_address`
PC file `/etc/hosts` adds line: kuri_ip_address kuri-0000328

Table 5.1: Remote Control Configuration

Algorithm 2 Robotics Control

```
1: procedure ROBOT_CONTROLLER
                                          ▷ initialize ros subscribers
2:     Initialize robot_pose_subscriber
3:     Initialize human_pose_subscriber
4:     Initialize imu_subscriber
5:     Initialize touch_subscriber
6:     Initialize robot_state_subscriber
                                          ▷ initialize ros publishers
7:     Initialize robot_current_state_publisher
8:     Initialize robot_vel_publisher
9:     Initialize robot_theta_publisher
                                          ▷ ros control loop
10:    while ros :: ok() do
11:        if robot_state = go_to then
12:            robot goes to waypoint with pid control
13:        if robot_state = pattern then
14:            robot moves in patterns
15:        if robot_state = turn_to then
16:            robot turns to a point with pid control
17:        if robot_state = idle then
18:            robot stops moving
19:        publish robot_current_state
20:        publish robot_velocity
```

The manual control is implemented with ROS node that publishes Twist message to the topic `/cmd_vel`, which is subscribed by the built-in ROS node on the robot's Linux kernel. This node doesn't run in the robot's autonomous state and needs to be started by the kuri_edu pacakge with the script "roslaunch kuri_edu kuri_edu.launch". In addition, the ROS node for manual control is running on an Linux PC that shares the same Wi-Fi with the robot so that they are in the same

distributed ROS network. In order to enable the remote ROS communication, additinoal configurations are needed as shown in table 5.1. The environment variables `ROS_IP` and `ROS_MASTER_URL` needs to be set on the PC. Also, the configuration file `/etc/hosts` on the PC should include the line "kuri_ip_address kuri-0000328" (eg. 172.19.179.47 kuri-0000328) to enable the Linux PC to subscribe to and receive messages from robot's rostopics.

Robot's autonomous navigation is implemented with a controller ROS node that makes decision on robot velocities by constantly detecting its current pose and comparing with the target (Algorithm 2). The controller ROS node subscribes to waypoint pose and tracking results of robot pose and human pose. Two PID controllers are adopted to calculate the linear and angular velocities respectively. PID stands for Proportional–Integral–Derivative and ensures that the robot doesn't overshoot the waypoint. A maximum speed is set to ensure that the robot doesn't move in an unexpected speed.

To calculate the angular velocity, the node uses ROS API tf to translate the rotation quaternion of robot pose into Euler angles roll, pitch and yaw. Next, the node compares robot's yaw angle with the included angle between robot and waypoint. The angle difference is calculated and fed into the PID controller for the final angular velocity. To calculate the linear velocity, the node compares the Eular distance between the robot and waypoint, and feed the distance into the linear velocity PID controller. Tuning PID controller is a necessary step to ensure that the robot moves in an desired way.

Robot Pattern Control

For the interactive pattern drawing, the robot moves in patterns such as cricle, line, helix and wave. This type of movements is controlled with scripted velocities at a certain time, as described in figure 4.5 and figure 4.6.

Simulator

Two simulation platforms for Kuri robot are Gazebo (figure 5.5) and Maya (figure 5.6). Gazebo simulator is implemented for easier testing and function development in ROS, while Maya is used to design Kuri's expressive animations with a Kuri model plugin provided by the company. In Maya, animation is created by setting key frames for robot motor states and exported to an animation file. Particularly, the animation file should be sent to particular folders on robot Linux kernel. The file access also needs to be modified with chmod in Linux in order to have executable access. It is expected that Kuri robot will have the same physical movement as the animation created in Maya. The reference for animation creation is hosted at the company's github repository [32].

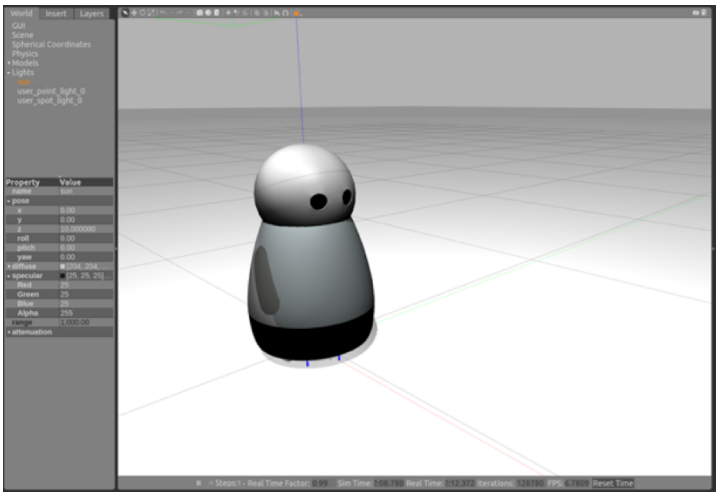


Figure 5.5: Kuri Robot in Gazebo Simulator

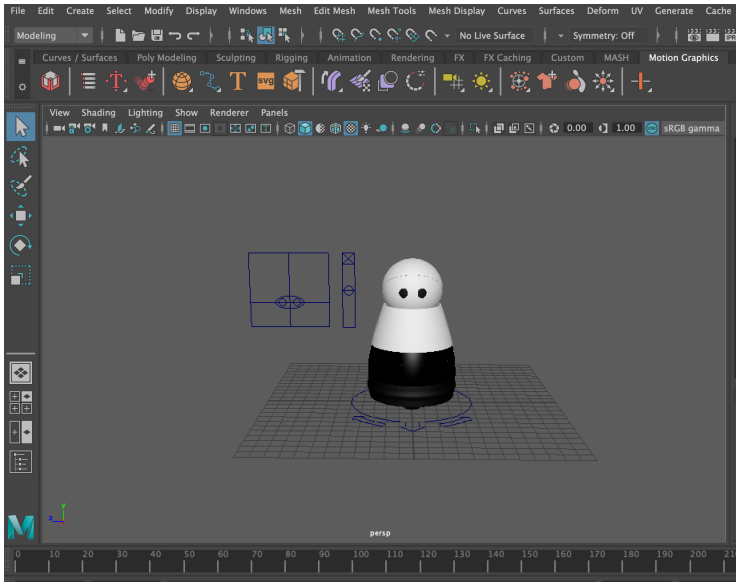


Figure 5.6: Kuri Robot in Maya

5.4 Computer Graphics

openFrameworks is a creative toolkit written in C++ built upon OpenGL. As shown in Algorithm 3, the overall program follows the structure setup(), update() and draw(). Such structure updates visual elements information such as color and position in every frame with an infinite loop. This thesis implements the interactive computer graphics with openFrameworks and combines it with tracking and robotics control with communication protocols in ROS.

Algorithm 3 Projecting Interface

```
1: procedure SETUP()
                                              ▷ initialize ros animations
2:     setup cheerful_anims, lost_anims
3:     setup curious_anims, attention_anims
                                              ▷ initialize ros subscribers
4:     Initialize robot_pose_subscriber
5:     Initialize human_pose_subscriber
6:     Initialize robot_theta_subscriber
7:     Initialize robot_current_state_subscriber
                                              ▷ initialize ros publishers
8:     Initialize robot_animation_publisher
9:     Initialize robot_state_publisher
                                              ▷ initialize pattern icons on canvas
10:    Initialize robot_pattern_list
11: procedure UPDATE()                        ▷ update robot state and visual elements
12:    update animation_time_gap
13:    update robot_state                     ▷ update both past and current trajectories
14:    update robot_trajectory
15: procedure DRAW()                          ▷ draw all visual elements on canvas
16:    draw robot_trajectory
```

Chapter 6

User Study

6.0.1 Experiment Venue



Figure 6.1: Shaprsburgh Community Library, Pittsburgh, PA

Participants from age 6 - 12 years will be recruited to participate in the user study. However, the city is in the mid of lockdown due to COVID-19 and the user study will be scheduled once the library reopens.

6.0.2 Experiment Design

With research question "How would social behaviors of a robot influence children's willingness to explore in the digital art making?", there are two experiment conditions as shown in 6.1: robot with social behaviors and without social behaviors. The current experiment is based on the interaction design concept of pattern drawing with the robot.

- Dependent Variable: Children's willingness to explore
- Independent Variable: Social behaviors of the robot

Situations	**Social Robot**	**Non-Social Robot**
The kid triggers a new pattern.	The robot displays cheerful look before drawing.	The robot starts to draw right away.
The kid blocks the robot path.	The robot displays lost look.	The robot stops moving until it's not blocked
No new pattern is triggered for a long time.	The robot displays curious look.	The robot stays idle.

Table 6.1: Two Experiment Conditions

Experiment Process: As shown in figure 6.2, here are two rounds of interaction for each participant, i.e. training trial and experimental trial. In the training trial, the experimenter only demonstrates pattern triggering by interacting with the canvas, then the participant interacts with the robot to draw for five minutes. Next, in the experimental trial the experimenter demonstrates the new way of pattern triggering by petting the robot head and informs the participant that it is unknown which pattern would be triggered in this way. Then the participant interacts with the system again for five minutes. After the two sessions, the experimenter conducts post study interviews with the participant.

Metrics: In the training trial, children's exploration will be evaluated by counting the number of patterns they have triggered through interacting with the canvas. In the experimental trial, children's exploration will be evaluated by counting the times they trigger the patterns through petting the robot, as they don't know what the pattern will look like ahead of time. In addition, post-study surveys and interviews will be conducted to get insights on the overall art making experience and their perceptions on the social robot. The questionnaire and interview questions are attached in the appendix.

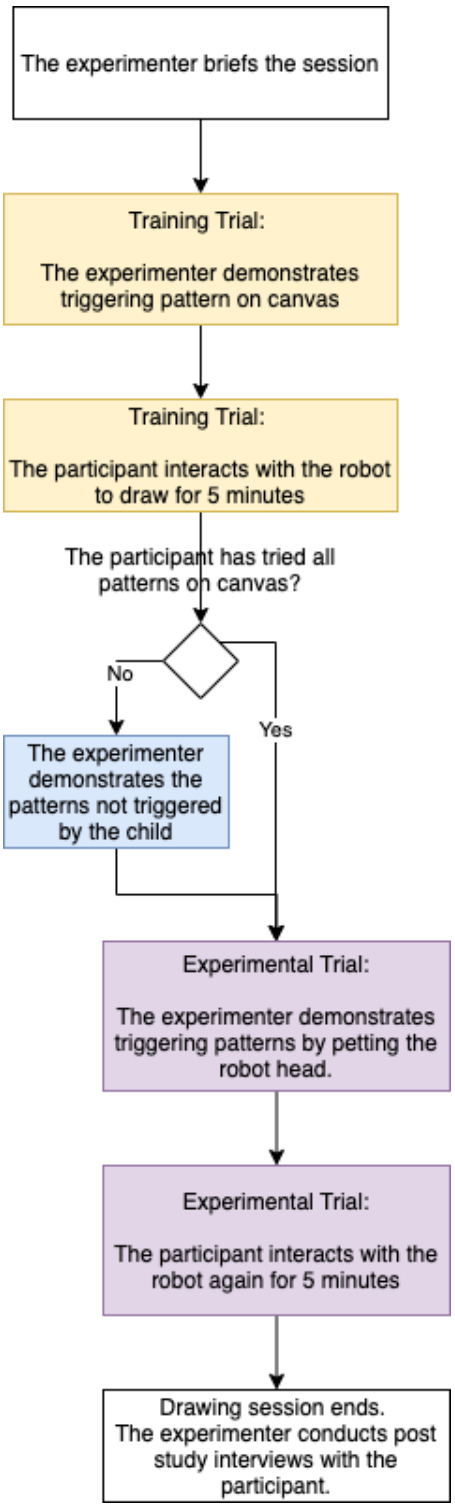


Figure 6.2: Experiment Process Flow

Chapter 7

Discussion

Limitation and Future Work

The most important next step is to perform user study with children and collect empirical data for analysis. The user study session will be recorded and the collected videos will be coded for further analysis. It is expected that the empirical data could provide new insights for children's exploration during the interaction, particularly their behaviors relevant to human robot interaction such as petting, path blocking, eye contact, etc. Besides children's exploratory behaviors, their perception on the robot will be evaluated with post study surveys and interviews.

Besides, the technical system could be further improved for more robust performances. The first possible technical improvement is tracking. Currently an RGBD camera from the hybrid view is used for location tracking, but the coverage for the depth sensor is limited by the ceiling height and the camera's field of view. The result accuracy is also affected by the depth image distortion. To increase the tracking accuracy, RGB image could be combined in addition to the depth information. Further image processing such as depth image undistortion could be conducted to improve the tracking results. Besides, other indoor tracking techniques such as Bluetooth beacon could be investigated. The second possible technical improvement is calibration. When changing installation venues, the technical system needs to be modified to adapt to the new environment. As the installation height and mounting positions for the projector and camera will change, a new round of camera calibration and projection mapping is required each time. Currently the parameters are adjusted manually, but the process can be automated to improve efficiency for relocation.

Lastly, the interaction design could go through more iterations with user pilot testing for the drawing mechanism, robot behaviors and timing for social animations. It is expected that involving users in the design phases could provide more design insights as well test the feasibility of the overall interaction mode.

For the robot social behaviors, they are triggered regardless of the robot's orientation in the current implementation. Another approach is that the robot rotates

to face the participant before the social behavior is triggered, which may increase the perceived animacy of the robot in the social condition. Another potential future step is to evaluate the level of expressivity of animations under the same category. For example, the animations with type "Look Cheerful" is randomly picked from the list when "Look Cheerful" behavior is triggered in the current system, but the animations may have different cheerful levels. Ranking expressivity of animations could help to design the robot social behaviors in a more customized way. In some cases, the low level of cheerfulness might be more appropriate than the high cheerful level or vice versa.

In terms of the timing to trigger social behaviors, the current design defines a minimum ten-second time gap between two robot animations as the robot may look strange if the social behaviors are triggered too frequently. However, the time gap for the robot to behave naturally could be further evaluated and be customized for different animations.

Contributions and Summary

The thesis presents an augmented system with a projector and a mobile social robot. Robot movements and social cues are incorporated in the interaction for children to engage in digital art making. In addition, the augmented system is implemented with three technical components, i.e. human and robot tracking, robotics control and interactive computer graphics. The system allows for multiple movement patterns of the robot for interactive art making as well as robot autonomous navigation in the projected space. The participant interacts with the system through the projected canvas or by touching the robot head. Further, the thesis develops the experiment protocol and metrics to evaluate children's behaviors with IRB approval. With the research question "How would social behaviors of the robot affect children's willingness to explore in digital art making?", the thesis provides two conditions for the interaction session, one is with the robot social behaviors and one is without.

In summary, this thesis aims to investigate the effects of using social robots for children's exploration in face of uncertainties. Built on the theory of constructionism that children make sense of the world by constantly exploring and interacting with their surroundings, this thesis presents an interactive system for children's exploratory activities. In face of the city lockdown, user study with children can't be conducted at the moment, but this is an important next step in the future.

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Appendix A

A.1 Survey Designed for Children

Talk about your art
I saw you _____ (using this pattern/composition/symbol etc.), why did you make in this way?
Which part do you like the most and why?

Exploratoriness in art making
Did you know you can choose different patterns/symbols/shapes/backgrounds? Why did you choose these ones?
If you have more time, would you keep going?

Confidence in art making
Would you show this art work to your parents? Friends?
How many stars would you give to your art?

★	★★	★★★	★★★★	★★★★★

What would you do different next time?

Perception on Kuri
What is Kuri's role? Where would you put a color palette/toy/kid/Kuri in the line below.



Do you think Kuri is good at art making?

No	Not bad	Yes!

Do you think Kuri helped you create better art?

Not at all	A Little	A lot

Do you think Kuri has its own plan?

Not at all	Maybe	Yes
		

Do you think Kuri is proud of its art skills?

Not at all	A little	A lot
		

Does Kuri motivate you to try more patterns?

Not at all	A little	A lot
		

Do you enjoy making art with Kuri?

Not at all	A little	A lot
		

Do you think Kuri had fun making art with you?

Not at all	A little	A lot
		

Would you like to do it again?

	Yes	No	Maybe
Create digital art with Kuri			
Create digital art with my friends			
Create digital art on my own			

Evaluate the interactive system

How do you think it is different from drawing on paper? Which one do you like more?
If you were to keep making art in this way, what do you think could be better?

A.2 Interaction Design Concept

Palette III

Palette theme and robot behaviors The canvas has a space theme with starts, sun and moon. Meteor shower animation can be triggered. Stars are draw by the robot's trajectory.
Interaction mode 1. Robot mirrors the participant's movement and leaves trajectories on the canvas. 2. Canvas background becomes dark blue if the robot hits the moon, becomes light orange if hitting the sun. 3. If the robot gets into participant's region, the region will become active for drawing. 4. If the robot hits canvas edge, a meteor shower animation will happen. 5. If the participant moves too fast, robot stays still.
Robot behaviors under social condition 1. Robot cheers once it hits the sun or moon that triggers background change. 2. Robot looks around as it is moving.
Expected explorative behaviors from participants 1. Figure out the mirroring behaviors of robot 2. Lead the robot to hit moon and suns to change background 3. Lead the robot leaves its starting area and triggers the other side for drawing

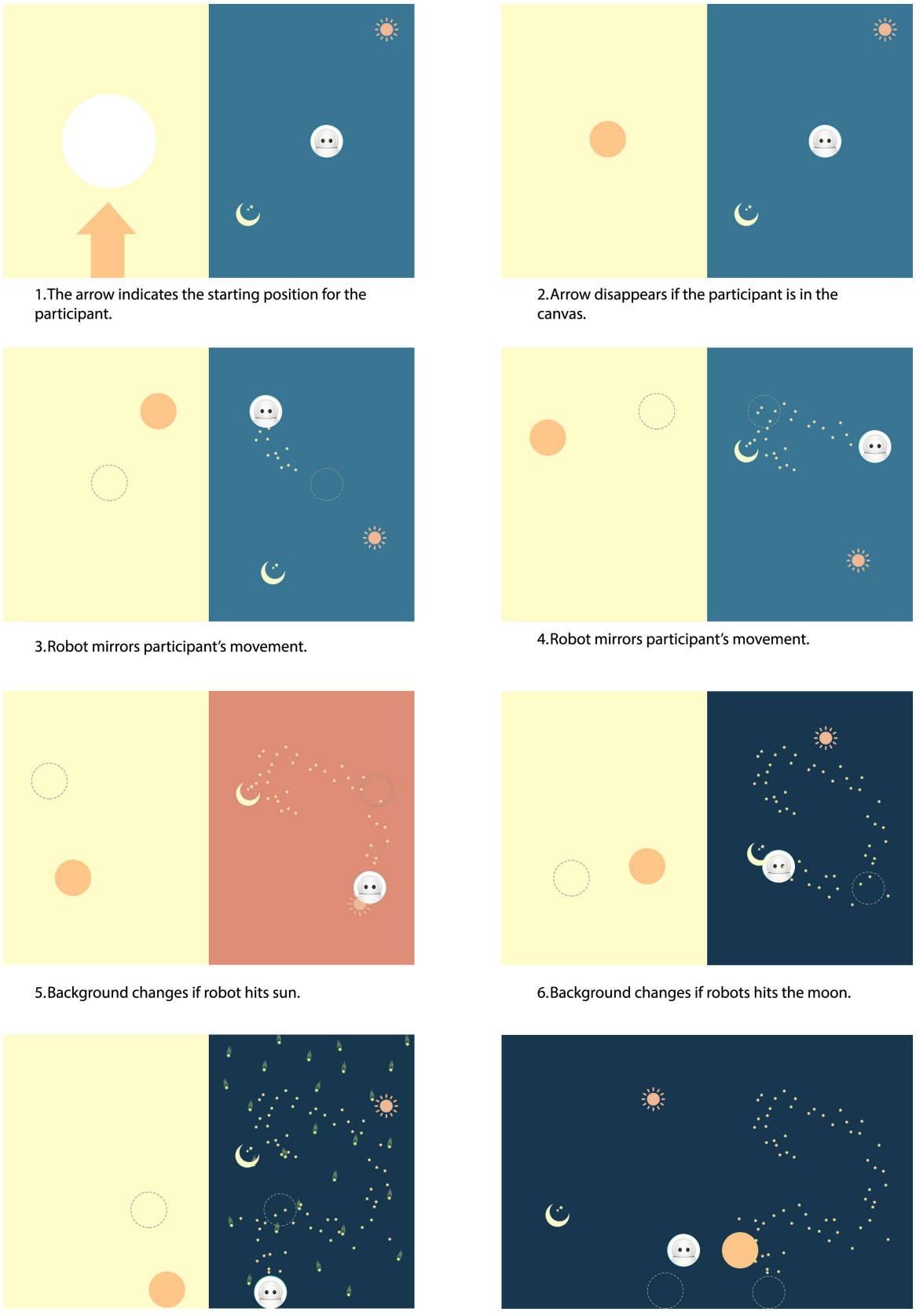
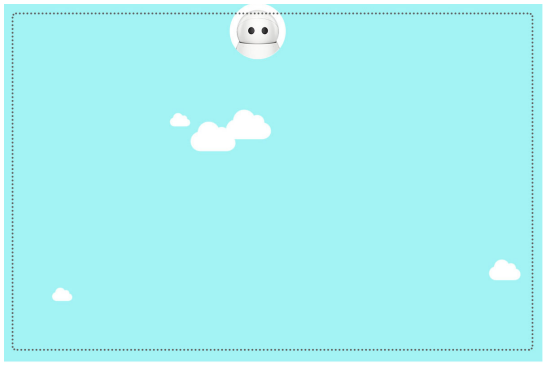


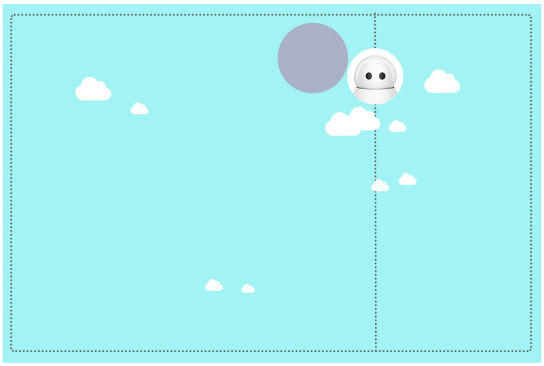
Figure A.1: Interaction Design for Palette II

Palette IV

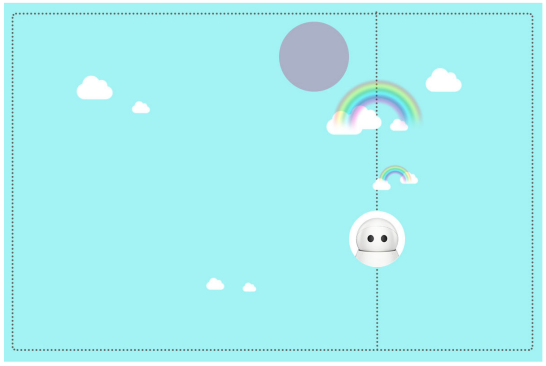
Palette theme and robot behaviors The canvas has a sky theme with clouds and rainbows. Robot moves along the canvas edge and move into canvas if triggered. Rainbows are drawn if the robot steps on clouds.
Interaction mode 1. If the participant touches robot head, it turns 90 degree and moves into the canvas. 2. If the participant steps on existing rainbows, more clouds will be generated. 3. If the participant blocks robot's way, robot turns around and move in the opposite direction.
Robot behaviors under social condition Robot looks around as it moves.
Expected explorative behaviors from participants 1. Touch robot head to change its movement. 2. Block robot path to change robot moving direction.



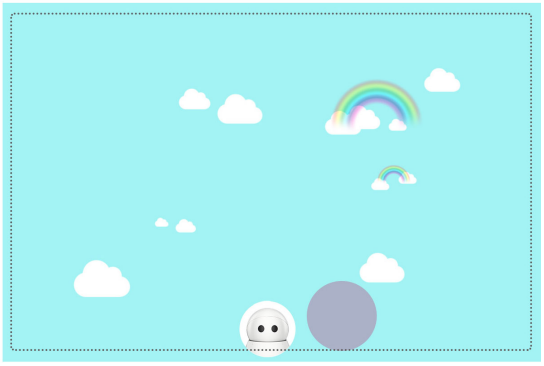
1.Robot moves along the canvas edge



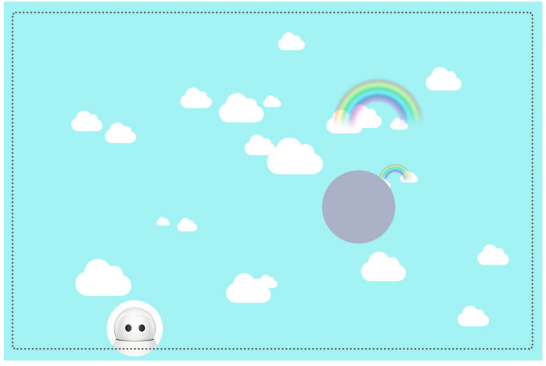
2.Robot moves into the canvas if the participant touches robot head.



3.Rainbow is drawn if the robot steps on the cloud.



4.Robot moves back to canvas edge after drawing the cloud.



5.More clouds are generated if the participant steps on the rainbow.

Figure A.2: Interaction Design for Palette IV