Developing a Semi-autonomous Robot to Engage Children with Special Needs and Their Peers in Robot-Assisted Play

by

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Author's Declaration

I hereby declare that I am the sole author of this thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

I understand that my thesis may be made electronically available to the public.

Abstract

Despite the wide variety of robots used in human-robot interaction (HRI) scenarios, the potential of robots as connectors whilst acting as play mediators has not been fully explored.

Robots present an opportunity to redefine traditional game scenarios by being physical embodiments of agents/game elements. Robot assisted play has been used to reduce the barriers that children with physical special needs experience. However, many projects focus on child-robot interaction rather than child-child interaction. In an attempt to address this gap, a semi-autonomous mobile robot, MyJay, was created. This thesis discusses the successful development of MyJay and its potential contribution in future HRI studies.

MyJay is an open-source robot that plays a basketball-like game. It features light and color for communicative feedback, omni-directional mobility, robust mechanisms, adjustable levels of autonomy for dynamic interaction, and a child-friendly aesthetically-pleasing outer shell.

The design process included target users such as children with special needs and therapists in order to create a robot that ensures repeated use, engagement, and long-term interaction. A hybrid approach was taken to involve stakeholders, combining user-centered design and co-design, exemplifying that children can be included in the creation process even when it is not possible to hold in-person co-design sessions due to COVID-19.

Aside from the care taken to meet user requirements, the robot was designed with researchers in mind, featuring extensible software and ROS compatibility. The frame is constructed from aluminum to ensure rigidity, and most functional parts related to gameplay are 3D printed to allow for quick swapping, should a need to change game mechanics arise. The modularity in software and in mechanical aspects should increase the potential of MyJay as a valuable research tool for future HRI studies.

Finally, a novel framework to simulate teleoperation difficulties for individuals with upper-limb mobility challenges is proposed, along with a dynamic assistance algorithm to aid in the teleoperation process.

Acknowledgements

I would like to thank professor Kerstin Dautenhahn for her timely and consistent support throughout this project. Her trust, excellent supervision, and vast knowledge in the field, helped me in developing the robot and making it a reality. It was a joy to work in her lab as a graduate student.

I would also like to thank my lab-mates for their unconditional support throughout the project and for making the master's experience such a joyful one.

This research was undertaken, in part, thanks to funding from the Canada 150 Research Chairs Program and thanks to NSERC Alexander Graham Bell Canada Graduate Scholarships.

Finally, and most importantly, my parents and brothers have been an anchor of unwavering support and encouragement throughout the project. This thesis would not be possible without them.

Dedication

This is dedicated to my parents and brothers.

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Chapter 1

Introduction

Children with special needs face barriers to play with their typically developing peers. This is mainly due to the difficulty of creating games that are fun and engaging to both demographics. Creating such games entails keeping a game challenging enough for both demographics without being too difficult as to not lose their interest. Robots are a great fit for in-person games as they are physical agents that can modulate difficulty whilst using their various embodiments to avoid being intrusive to gameplay. If designed carefully, robots can be inclusive to children with special needs without compromising on the "fun" factor that is essential for the success of any game. A "fun" game would be successful in pulling the attention of children regardless of their physical abilities and would be able to connect children together and engage them in social interaction.

With the aforementioned statements in mind, research questions for this project were formulated as the following:

RQ1: How can we exploit robots to create joyful play sessions that facilitate human connection for children with different levels of physical abilities and needs?

In the process of creating a robot to answer RQ1, two sub questions pertaining to the robot's teleoperation and control aspects were formulated:

- **RQ1.1:** Can we simulate robot teleoperation difficulties that face individuals with special needs, specifically upper limb mobility challenges such as cerebral palsy (CP)?
- **RQ1.2:** Can we use expert feedback during teleoperation to build an adaptive assistive system that does not interfere with gameplay?

Additionally, children were included in the design process by interviewing them for feedback. The interviews were motivated by the following research question:

RQ2: How can we involve children with physical special needs, specifically children with upper limb challenges, as part of the design process of inclusive robots for robot-assisted play?

RQ1 is addressed in chapter 3, and questions RQ1.1 and RQ1.2 are addressed in chapter 5. RQ2 is addressed in chapter 4.

1.1 Motivation

As mentioned earlier, children with special needs face difficulties participating in games with their typically developing peers such that both groups are engaged. This may leave children with special needs such as those with physical challenges stuck playing games on screens, or playing games with their families, instead of playing with children in their own age group. It is important to ensure that play activities are accessible and guarantee equity, and inclusivity without putting an extra burden on caregivers. Play scenarios should also avoid differentiating between children with and without accessibility needs. Including all children in play enables *peer directed interventions*, in which, typically developing peers who have learned social communication strategies are paired with children with special needs during play; which can promote social communication in children with disabilities [2].

There are many great robot-assisted play examples in HRI (discussed in chapter 2). Robot-assisted play scenarios in HRI are typically focused on child-robot interaction rather than child-child interaction. The robot presented in this thesis was designed specifically to facilitate child-child interaction. The intention here is not to reject systems that focus on child-robot interaction, but rather to explore different avenues in hopes of promoting fun and organic interaction between children with physical special needs and their peers. MyJay is designed to be used in public settings such as schools, community centers, therapy centers and hospitals.

1.2 Proposed Contribution

As Robots open possibilities for accessible play with their perception abilities, autonomy and flexibility of control methods, we designed MyJay to have socially evocative features, whilst still being fun and inclusive.

The robot can be fully teleoperated or used as a semi-autonomous agent depending on ability or skill level of the player; this keeps children continuously engaged at the right level of challenge. Besides accessibility, emphasis was placed on mechanical robustness, attractive design and modularity in software. The robot is built from off-the-shelf parts along with some functional 3D printed parts. The shell was designed for manufacturing on small hobby-level 3D printers and can be mounted on the robot securely. An important goal of this project, was to develop a robot that can be replicated by others by making final designs available open-source.

It is important to note that MyJay has not been tested with children with special needs due to restrictions imposed by COVID-19. This however, did not prevent us from including them in the design process remotely. The work presented in this thesis needs to be validated with the target user group in order to ensure effectiveness and iterate on the design.

Finally, a novel method to simulate robot teleoperation by individuals with special needs is presented. The proposed method could have potential to accelerate development of accessible technologies by allowing developers to test early iterations of their designs, and quickly prototype accessible solutions. Moreover, an *assistance as needed* (AAN) model is proposed to provide seamless and adaptive help to users of the robot depending on their teleoperation abilities.

1.3 Publications

As mentioned in the Author's Declaration section, parts of this thesis have been published or are in-review. One paper was published in the International Conference on Social Robotics (ICSR 2020) [3] where I discussed the motivation, design process and an overview of each subsystem on MyJay. My co-authors on the paper were of great help, namely, Omar Shariff assisted in the ideation of the intake and elevator mechanisms on the current version of MyJay, and Shahed Saleh wrote about her involvement in the design process of the shell and making sure that is user-friendly and implementable using 3D printing techniques.

A short paper was also submitted to the ICSR 2020 robot design competition [4], where MyJay won the 2nd place award in the "Innovation as potential responses to Covid 19 global pandemic" category. In the paper, I explored the motivation of MyJay in more detail and explained the potential of the robot for remote teleoperation.

Another short paper was submitted to and published in the pioneers workshop at the International Conference on Human-Robot Interaction (HRI 2021) [5]. The paper explored aspects of the robot design that we were not able to present in [3] due to space limitations. Shahed Saleh wrote about her work on the shell design and prototyping some light interaction on the robot, and I wrote about interface design and future directions for the work.

Finally, a paper has been submitted to the IEEE International Conference on Robot and Human Interactive Communication (RO-MAN 2021) and is currently in-review. In the paper, I discuss and analyze remote interviews I had conducted to obtain feedback regarding MyJay's design from children with special needs and their families. Shahed Saleh assisted in the audio transcription process, and Ellie Sanourbari assisted in the literature review process.

Professor Kerstin Dautenhahn oversaw the entire project and provided periodic supervision/feedback. She participated in the authorship process of all of the above papers.

1.4 Thesis Outline

Chapter 2 presents a literature review on the importance of play in child development, literature on robot-assisted play, difficulties that children with upper limb mobility challenges may face, adaptive robotic systems that compensate for mobility challenges, and a brief overview of user-centered design and co-design methods.

Chapter 3 discusses the development process of MyJay, and highlights design features of the robot.

In chapter 4, a remote interview study to get potential users' feedback is described. Procedures, findings and discussions as well as lessons learned from the study are presented.

Chapter 5 presents a novel approach to simulate gameplay of individuals with upper limb mobility challenges, and discusses an AAN paradigm achieved through learning by demonstration.

Finally, chapter 6 summarizes work presented in this thesis and presents potential future directions for this project.

Chapter 2

Literature Review

This chapter reviews the literature on benefits of play for child development, different robots used in robot-assisted play scenarios, brief description of upper limb mobility challenges and how they are addressed in Human-computer interaction (HCI) and HRI, and user-centered design and co-design techniques in the field of HRI.

2.1 Play and Child Development

2.1.1 Developmental Benefits

Play is important for child development. It promotes emotional skills, forming safe, and nurturing relationships with guardians and peers [6]. While there are many definitions of play, there is agreement on it being a voluntary, intrinsically motivated activity with the following characteristics: unfinalisation, creativity, non literalness, flexibility and pleasure [7]. Play teaches children to focus on tasks at hand without exposing them to stressful situations; it demands commitment and seriousness while maintaining a dividing line from reality: "Play demonstrates that two different attitudes co-exist: to be fully involved in what one is doing and to be aware of the fact that we are within a relative, delimited and conditioned dimension" [8]. Play supports many developmental functions such as adapting to new situations and environments, and looking for solutions especially when a novel situation is presented in which a child has to think critically [7]. Another function of play is to place children within a cultural context where they have to understand the flexibility of roles and rules in society [7], which is important for the development of social skills.

Additionally, play is essential for sensorimotor development; manipulation of objects enhances sensorimotor coordination where actions are linked to physical achievements [7]. This cyclic relationship between motor actions and manipulation of environment changes perception and leads to new modified actions, which appears clearly in newborn children [9]. In addition, play is important for cognitive development, engaging higher symbolic functions such as language, graphical representation and narrative ability [7]. Perhaps one of the most influential aspects of play on a child's development is its role in psychological and emotional development; play allows children to explore a range of emotions and facilitates managing the stress of strong emotions which leads to less impulsive responses and better controlled actions [6]. Play supports emotional growth, pushing children to take risks, communicate with other players, negotiate rules, cooperate and learn how to win and lose in a gracious manner. Play is not simply for "fun". It is essential for child development; if a child cannot play, they do not learn sufficiently the necessary skills or gain the confidence and self esteem that are important to being able to lead an independent life, make friends or find a job.

Play benefits have been observed physiologically in brain structure and functioning. Play has been found to stimulate the production of brain-derived neurotrophic factor (BNDF) in RNA in the amygdala and dorsolateral frontal cortex [10]. BNDF has a role in the survival of neurons and supports synaptogenesis and the growth and differentiation of new neurons [6]. Additionally, it is important for long term memory and social learning [6]. Juvenile rats that were deprived of play were less competent in problem solving and had significantly less mature medial prefrontal cortex (PFC) which suggests a link between play and the process of synaptogenesis [11]. The PFC is critical in short-term memory and the preparatory action set [12]. Additionally, rats with physically normal brain structure that were deprived of play at a young age showed similar social deficiencies as rats with PFC damage. Lower levels of cortisol are associated with elevated amounts of play which suggests a correlation between play and reduced stress [6].

2.1.2 Barriers to Play

There are many barriers that prevent children with physical special needs from participating in play activities with their peers. These barriers can be classified into personal, social, environmental and policy barriers [13]:

- **Personal barriers** include lack of physical and social skills to participate in activities with their peers [14, 15], and they also include some internal barriers such as fear and dislike of being judged due to their disability [16].

- **Social barriers** are often related to popular beliefs/stigma regarding disabilities. For example, twenty one percent of parents of children with spinal bifida (a disease in which the spinal cord and nerves are damages [1]) and eight percent of parents of children with cystic fibrosis (a disease where linings of the airways, digestive tract, and other organs and tissues have sticky mucus that can build up and lead to blockages, damage, or infections in the affected organs [2]), believed that physical and recreational activities are more important to typically developing children without disabilities [17].
- **Environmental barriers** refer to the lack of accessible facilities and/or lack of adequate transportation [13]. For example, Toronto, a large metropolitan city with lots of focus on accessibility still lacks adequate accessibility options. A passenger with spastic diplegia cerebral palsy (which affects muscle control and coordination), reported to the Toronto Star "I see that they're really trying and a good number of stations are accessible, but not as many as should be or could be" [3].
- **Policy barriers** refer to the lack of programs, funding and staffing to host activities that accommodate children with special needs.

Often, the problem is multi-factorial, and a variety of barriers are present at the same time. For example, most toys are not accommodating for children with Cerebral Palsy (CP) or muscular diseases, and as a result, they are difficult for them to manipulate, rendering play activities difficult [18]. This causes children to need support to participate in play activities, or pushes them into passive play roles. This problem is prevalent as there are many different medical conditions causing barriers to play. For example, About 1 in 323 children has been identified with Cerebral Palsy in the USA [19], and that's just one of many possible medical conditions hindering children from play.

In this project, I attempt to address barriers facing children with physical special needs such as CP. These conditions typically come with both mobility and manipulation difficulties, and affected children are less likely to engage in play activities with their peers.

2.1.3 Cerebral Palsy

I was initially unsure about which medical condition to focus on, especially with the pandemic as I was not able to test the robot with children. When recruiting for an online study

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[1] https://www.cdc.gov/ncbddd/spinabifida/facts.html

[2] https://www.nhlbi.nih.gov/health-topics/cystic-fibrosis

[3] https://www.thestar.com/news/city_hall/2019/03/10/a-look-at-ttc-accessibility-through-the-eyes-of-
html

with the criteria: "upper-body gross and fine motor special needs", most participants were affected by CP. I suspect this was due to the project meeting the needs of children with CP the best.

With the above in mind, it is important to understand what CP entails. The most cited definition of CP, which dates back to 1964, is the following: *"a disorder of posture and movement due to a defect or lesion in the immature brain"* [20]. However, given the complex nature of the disorder, and the rapidly evolving medical knowledge and diagnosis technology, this definition was revised in 2004 to the following: *"Cerebral palsy describes a group of permanent disorders of the development of movement and posture, causing activity limitation, that are attributed to non-progressive disturbances that occurred in the developing fetal or infant brain. The motor disorders of CP are often accompanied by disturbances of sensation, perception, cognition, communication, behaviour, by epilepsy and by secondary musculoskeletal problems"* [21]. This is a much more comprehensive definition and allows us to account for perceptual, cognitive and communicative challenges when designing the robot.

It is important to note that CP manifests in many forms, resulting in a variety of physical ability levels across affected children. For example, hemiplegia which is the most common form of CP (around 38% of cases), is known to affect one side of the body and is sometimes referred to as unilateral palsy [22]. Hemiplegia can manifest in spastic or dyskinetic forms, with the spastic form being most prevalent. Another form of CP is diplegia, which affects both sides of the body such as both arms or both legs [22]. Addressing all needs is difficult, however, keeping different forms/challenges in mind, and including target audience in the design process are keys to ensuring designs are useful and receive long term adoption.

2.2 Robot Assisted Play

Robots are becoming increasingly popular tools of entertainment for children, especially for those with special needs, and often embedded in an educational or therapeutic context. Children with special needs often experience difficulties in performing play activities in an organic way [23]. Many projects have attempted to address children who have barriers to play due to special needs through the use of robotics [24]. For example, PlayROB is a three axis teleoperated robot that enables children with severe physical disabilities to play with LEGO bricks [25]. The robot's construction bears resemblance to 3D printers with its stationary base and linear axis motion as shown in Fig. 2.1. The simple, 3 degree-of-freedom (DOF) cartesian configuration of the robot allowed it to be easily understood and teleoperated by children. Teleoperation devices included 5-key switches, head switches or joysticks depending on the user, and one child used it with a single switch input device. LEGO bricks are stored vertically and drop through gravity without any actuation which reduces cost and further increases safety. Prior to testing with children, the system was tested by experts to find any issues and eliminate them in order to reduce frustrating children in actual trials. A two-year long term study showed no decrease in interest, and reported high concentration and fun [26]. Despite the positive feedback from children, the authors reported that the daily schedule at these schools already is very busy and that there was some lack of teaching staff that have time to coach children while playing with the robot [26].

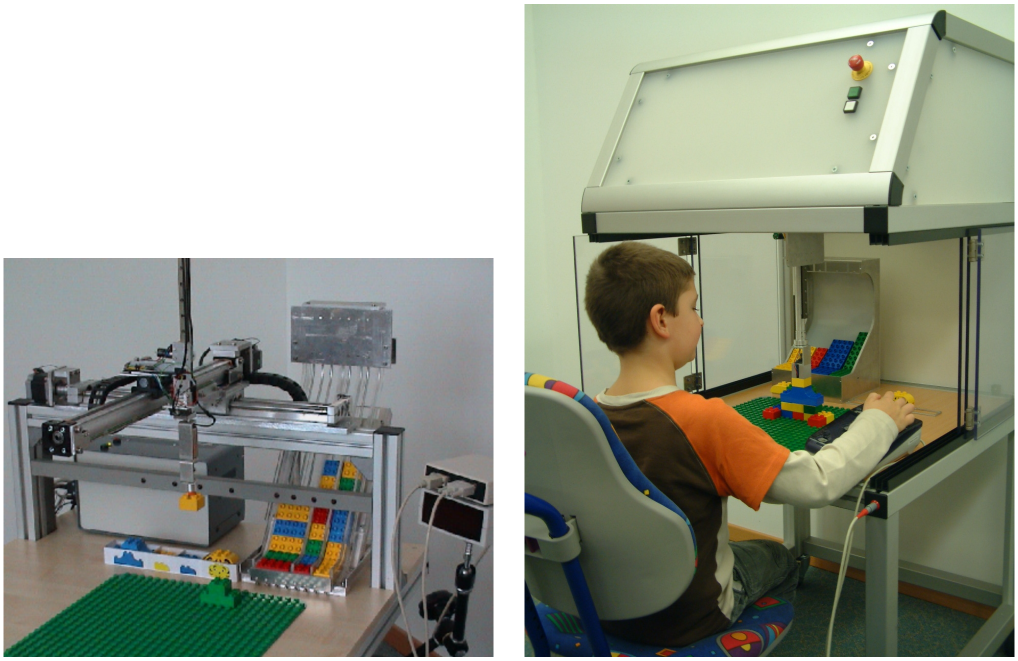
(a) (b)

Figure 2.1: (a) Prototype of PlayROB, the robot assistant, and (b) shows the second iteration of the robot, enclosed for increased safety/presentability. The robot allows children with severe physical disabilities to play with LEGOs. Obtained with permission [25]

Another example is the mobile IROMEC robot, which is the result of a European project that investigated the role a robotic toy can play as a social mediator for children who have barriers to play due to cognitive, developmental or physical impairments [27],

[28]. The IROMEC robot is mobile and allows for a number of play scenarios such as *Follow-me*, *Bring me the ball*, and *Tickle* [29]. In addition to the mobile configuration, it has a stationary, upright (human-like) configuration which allows for imitation games such as *Dance with me* [29] as shown on the left in Fig. 2.2. It is equipped with sensors for obstacle detection, navigation and color tracking. Additionally, it has buttons for interaction and two display screens: a body (touch screen) and a head. It uses the screens for interaction and displays a cartoon-like character [30]. The modular, user centered design of the robot allows for solitary and group play, and seemed to facilitate gross motor skills, walking, turning and balance, as well as stimulating enthusiasm, social interaction, communication and action [28]. Marti (2010) used the robot to implement perceptual crossing, a concept where perceiving others is an interdependent activity where others are perceiving the observer as well, or in other words, *"Perceiving While Being Perceived"* [29]. For example, when a person enters a room, and the robot is autonomously navigating,if the person crosses the robot, the LEDs light up and follow the person passing by. This creates a sense of intentionality in the robot that the user can perceive and understand, enhancing communication.

Figure 2.2: Different configurations of the IROMEC robot. (a) shows the digital face configuration, and (b) shows a static, pre-designed face. Obtained with permission (courtesy of Prof. Patrizia Marti, University of Siena).

LEGO robots have been explored for play in children with limited motor ability and for education via speech generated communication [31, 32, 33]. The use of a custom LEGO robot resulted in independent play, display of positive joint attention and enjoyment to a eight-year old with severe physical disabilities [32]. The child used his head to activate switches to interact with the robot. The mobile robot Cosmobot utilized voice input and targeted children with learning and developmental disabilities [34]. It was designed to be used by therapists and focused on motivating children with special needs to interact with the environment and facilitate therapy sessions. URSUS is a teddy bear-like robot that was designed for training of children with motor impairments [35]. Maggie is a doll-like, social robot created to explore mechanisms of interaction with humans [36] and supported a variety of games [37]. While Maggie was not designed specifically for children with special needs, it is another example of robot-assisted play.

Kaspar is a minimally expressive robot designed for playful interaction, specifically, for children with autism [38]. Its child-like appearance and size allowed it to act as a social mediator for collaborative play and facilitated interaction and role switching [38]. It was used in many therapeutic play scenarios targeting chidlren with autism such as promoting body awareness, mediating child/adult interaction, helping children to break isolation, and managing collaborative play. Collaborative play was facilitated through the use of a remote control to teleoperate the robot. One child would use the remote to control the robot's movements, and the other would imitate the robot. Children got to experience turn taking and role switching, and even learned to "let go" of the remote to give it to others. While robot-assisted play for children with autism is not the focus of this thesis, KASPAR offers some interesting lessons on collaborative play. Other robots designed for children with autism spectrum disorder (ASD) include Romibo [39], Kiwi [40], Robota [41], RoboParrot [42], BLISS [43], WAS-5 [44], Bandit [45], ELE [46] and Troy [47].

While most robots developed in research projects are currently not commercially available [24], ZORA is a commercially available robot based on the popular NAO platform with special simplified software [48]. Its humanoid form factor and toy-like appearance allow it to be used in a variety of applications such as companionship or creating basic games. Additionally, commercial pet-like robots can be used as toys such as the Pleo robot [49] and the newly re-released Sony Aibo [4]. These robots, though used in play, offer companionship as their main selling point.

It is worth noting that many of these systems mainly focus on solitary play, which is quite important in some cases. However, human-human interaction is quite important and should be accounted for in the design process. Robots such as IROMEC and KASPAR have scenarios where group play is central [38][1]. This is quite important in order to avoid

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[4] https://us.aibo.com/

social isolation especially in children who have limited access to play with their peers. In this project, we designed a robot geared specifically towards group/peer play. The project aims to include both children with and without physical special needs. We attempt to design a game that is fun and supports long term adoption of the technology.

2.2.1 Play Types

Play can be classified into many types but in the context of play scenarios involving robots, Robins et al. have classified play into four categories: (1) Sensorimotor play which consists of repetitive muscle movements and may involve the manipulation of an object, (2) Symbolic play in which symbolic, non-literal roles are imposed on players, (3) Constructive play where the player engages in creation or teaches someone else how to do something, and (4) Games with rules which constrain the actions and reactions of players [1]. Play can be solitary or in a group. Group play can be either competitive or cooperative. A study involving an educational math game found that competitive and cooperative play had greater interest and enjoyment compared to individual play [50]. Additionally, collaboration resulted in stronger intentions to play the game again and to recommend it to others [50]. Creighton and Szymkowiak found that cooperative games may benefit the social interaction of pupils within the classroom [51]. Taking the literature into account, we decided to focus on sensorimotor play due to its importance in developing object manipulation abilities. The activities will take place in a group setting to facilitate growth of social skills and connect children with their peers.

2.2.2 Robotics Competitions

This project took a lot of inspiration from the international robotics competition, FIRST Robotics Competition (FRC). FRC is organized by the FIRST (For Inspiration and Recognition of Science and Technology) organization, and is a yearly recurring challenge which allows high school students lead by volunteer professional mentors to create robots to solve a specific task. Tasks or "games" are typically sports themed such as robots throwing balls, basketballs and Frisbees. The following is an excerpt from the FIRST website: *"Combining the excitement of sport with the rigors of science and technology. We call FIRST Robotics Competition the ultimate Sport for the Mind. High-school student participants call it "the hardest fun you'll ever have.""* [5].

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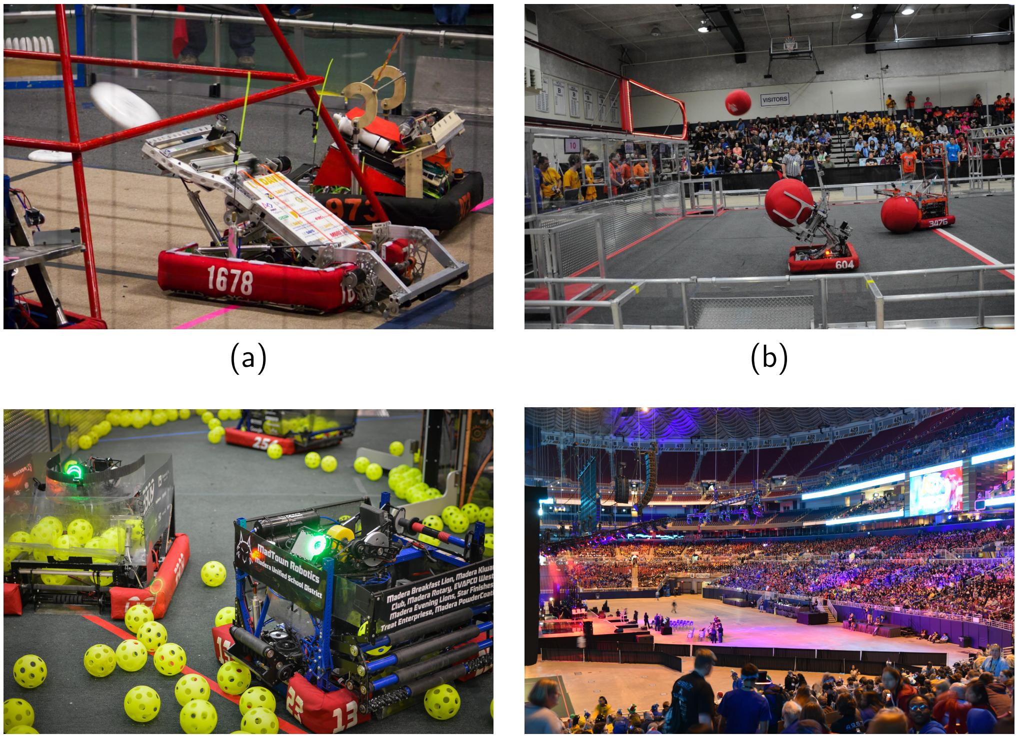
[5] https://www.firstinspires.org/robotics/frc/what-is-first-robotics-competition



(a) (b)

(c) (d)

Figure 2.3: Various FRC Robots and Venues. (a) Robots from the 2013 game (Ultimate Ascent), (b) Robots from the 2014 game (Aerial Assist), (c) Robots from the 2017 game (Steamworks), (d) The FRC 2017 World's Championship, held in St. Louis, USA. All images are publicly available on https://www.team254.com/photos/.

Drawing inspiration from FRC games, we settled on a field-based game centered around robots scoring through collaborative and competitive efforts. Figure 2.3 shows examples of some past FRC robots and venues.

2.3 Robot Semi-autonomy

2.3.1 Assistance As Needed

At the heart of a semi-autonomous robot with teleoperation capabilities is a controller which provides assistance to the user. An adaptive system which modulates its assistance based on the user's performance is desireable as it encourages users to improve their performance and keeps the activity challenging/interesting. Such systems provide "assistance as needed" or AAN [52]. If the AAN system does not provided assistance when needed, the activity becomes too challenging and the user/player loses interest, but if it provides too much assistance, therapeutic benefits are not acquired and it could lead to "learned helplessness" where the spinal cord habituates to repetitive activation of the same sensory pathways [53].

Crespo (2006) implemented an AAN control strategy for simulated power wheelchairs where a force feedback joystick is used to apply forces to correct a child performing a "follow the line" task [54]. They provided force feedback based on the distance between the center of the wheelchair and the line being followed, the angle between the wheelchair heading and the ling, and the rate of change of the wheelchair's orientation. Their preliminary studies found that an AAN controller can reduce large steering errors which improves driving performance and potentially increases safety while still allowing children to learn to drive the wheelchair [54].

Duong et al. created a telerehabilitation teleoperation system which connected therapists with patients using a single DOF robotics manipulator on each user's end [55]. Therapists are able to provide (1) passive motion assistance by moving the master arm and have the robotic arm on the user's end follow the master trajectory, and (2) active motion assistance by allowing the patient to move their robotic arm and having the therapist (or program) assist or resist the patient's robotic arm by moving the arm on their own end. The two arms are linked via force measurements, and provide force feedback to users via an impedance controller [55]. The researchers guaranteed controller stability by setting the master arm's impedance so that the robot's system is always passive [55].

Adamovich et al. designed a bimanual assistive system for post-stroke patients as a training tool for arms affected by stroke. Similar to the system proposed in [55], this system utilizes a master-slave force approach, however, this master-slave relationship is between between the unimpaired and impaired arm, which encourages the user to actively move the affected arm during an activity [56]. The adaptive system modulates the level of assistance/haptic feedback given to the affected arm by measuring success rates of previous tasks, and applies trajectory smoothing during operation. The researchers showed the feasiblity of the system, and in a follow up study, they measured cortical activation using functional magnetic resonance imaging (fMRI) and found that the virtual mirror feedback recruited the lesioned (injured) hemisphere [57].

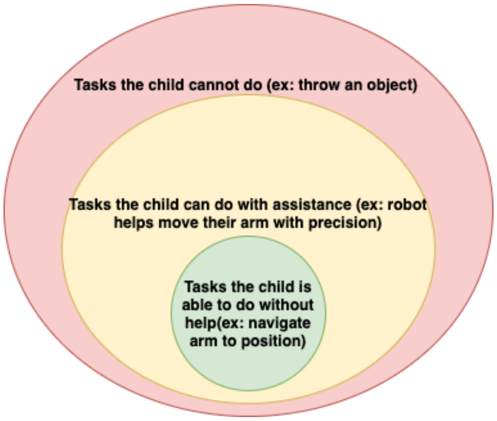


Figure 2.4: Example of the zone of proximal development (shown in yellow) for a child with upper limb mobility challenges such as diplegia.

In their paper *Knowing When to Assist*, Demiris discusses how an adaptive strategy would benefit from understanding the current level of the user, and their *potential* to grow and be able to perform certain tasks without robotics assistance [58]. He linked this to the idea of the Zone of Proximal Development (ZPD), a concept proposed by Vygotsky [59]. The ZPD is a collection of tasks the user is able to do when given assistance. A ZPD example is shown in Fig. 2.4. In order to incorporate the ZPD into an assistive wheelchair system, Demiris predicted user intention through Intended Task Inverse Models (ITIM), and evaluated whether the user's intended task falls within the ZPD. The wheelchair would then move based on the user's input and the output of the inverse model. More recently, Demiris has used learning from demonstration (LfD) to create a model that provides shared control [60]. Similar to to the force feedback systems used by Duong et al. [55] and Adamovich et al. [56], the wheelchair joystick in Demiri's system is a small robotic arm that is able to provide force feedback to the user. The expert/therapist has access to a similar robotic arm and provides assistance to the user, and the LfD algorithm learns from the expert's input. The results indicated that the model learned from the expert assistance through a single demonstration [60].

From examining the literature, it seems LfD has great potential for providing AAN in play sessions.

2.3.2 Learning from Demonstration

LfD outlines techniques used to learn a task policy from human demonstrators/teachers [61]. LfD offers the advantage of allowing experts in their respective fields to teach robots/algorithms to perform a certain task. For example, a therapist may teleoperate a robot to provide assistance to a patient attempting to grasp an object. The therapist can decide when to provide assistance based on their expert views of the patient's current level, or in other words, they would be providing AAN. Using LfD, we can teach a robot the appropriate level of assistance by using the therapist sessions as training data. Ideally, LfD should help generalize across different states as it is impractical to demonstrate every single possible scenario [61].

In terms of teaching, there three ways robots can learn: (1) learning by doing, (2) learning from observation, and (3) learning from critique [61]. Each technique has advantages and works for a set of applications depending on the robot's design, application and environment. The following is a brief summary of each technique:

- Learning by doing: this technique takes advantage of the teacher being able to directly control the robot's motion. One method is by direct teleoperation, which allows the teacher to use a joystick to move the robot in its environment while the robot records data from its on-board sensors. This approach has been used in many applications such as teaching a robot to navigate environments and avoid obstacles [62]. Other methods can substitute for teleoperation such as *kinesthetic learning*, where the teacher moves the robot's joints instead of teleoperation, and *shadowing*, where the robot mimics the body movements/trajectory of a teacher (whose actions are being recorded with sensors such as motion capture systems [63]).

- Learning from observation: in this technique, the teacher performs a task instead of controlling the robot directly, and their actions are mapped to the robot, making this technique effective with humanoid robots [61]. Although similar to shadowing, the robot here does not mimic the teacher simultaneously, and the focus is on the actions given the current state of the teacher and robot [61]. For example, the robot can track the position of a box being moved by the teacher, instead of mimicking the exact hand trajectory of the teacher. This technique can suffer from the *correspondence problem*, which deals with mapping actions from the teacher to the robot and transferring information between each other [64].

- Learning from critique: in this technique, the robot uses exploration to select actions, and gets critiqued by a human teacher, similar to *shaping*, a term in psychology which refers to training a person or an animal on a behaviour through positive or negative reinforcement [65]. Most methods in this technique rely on reinforcement learning (RL), which has the advantage of not needed the teacher's undivided attention [61]. On the other hand, it is arguable that the robot does not take enough advantage of the teacher's expertise [61].

In this thesis, teleoperation is an important aspect of interaction with the robot, and since the robot is mobile with a holonomic drivetrain, it is suitable to using the "learning by doing" paradigm, specifically through teleoperation.

2.3.3 Simulating Hand Mobility Challenges

Due to COVID-19, I could not conduct in-person experiments with children with special needs, however, I still wanted to be as inclusive as possible. Aside from interviews with children with special needs and their families, I conducted a literature review to check if it is possible to simulate a child with CP controlling the robot. Simulation is important as it allows to account for physical challenges even if we cannot conduct in-person studies with children. To the best of our knowledge, there has not been a system that simulates robot teleoperation for children with CP or other physical challenges. However, there is some relevant literature that could help us formulate such a simulation.

Nejafi et al. used a spring array to simulate controlling a master-slave robotic arm system by a child with CP [66]. The springs brought the joystick/robotic arm towards a static location to simulate the child using the arm to pull a box from a point A to another point B [66]. Their reasoning for using a passive spring array system was that the human hand dynamics have been modeled using spring arrays [67], and due to muscle stiffness in children with CP [21], it would be appropriate to simulate the hand movements of child with CP using a spring array for their particular task.

Biswas et al. designed a simulator to emulate elderly users and users with special needs while using electronic devices such as computers and TVs [68]. The goal of their system was to provide a tool to help user interface designers make inclusive design decisions. Through user modelling, the simulator embodies the internal, perceptual and cognitive state of a user as well as their motor processes [68]. In order to build their system, they collected data from users of various abilities and validated their simulations using data from real users. For users for cerebral palsy in particular, their simulations were based on the motor behaviour model, which was developed using cursor data from motor-impaired users [69]. The model assumes a mouse click task has 3 phases: (1) starting phase where the user gets control of the pointing device (ex: mouse), (2) middle phase which consists of a ballistic movement from the starting point to the target, and (3) homing phase where sub-movements home on the target [69]. The model output based on the 3 phase assumption is shown in Fig 2.5.

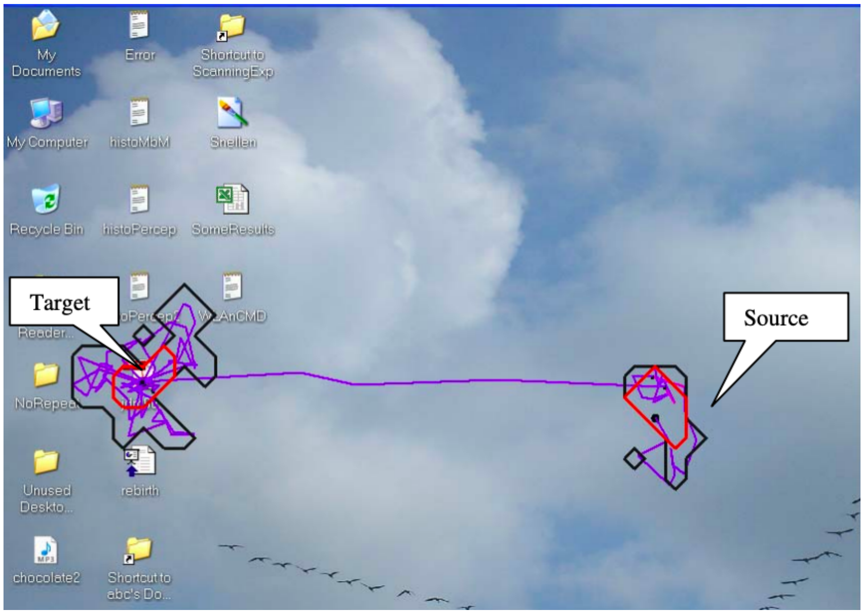


Figure 2.5: Example output of the motor behaviour model, simulating movement trajectory for a user with cerebral palsy. Obtained with permission [69]

Burgar et al. describe a series of experiments that were used to develop a patient-controlled robotic therapeutic device [70]. They compared healthy subjects to post-stroke hemiplegic subjects by seating them, supporting their forearms, and asking them to hold on to a robotic arm's end effector [70]. Subjects were asked to push with approximately one pound of force in a certain direction. They found that healthy subjects generated forces in the desired direction, while moderately and severely impaired subjects generated forces in lateral directions [70].

While two of the example discussed above do not involve children with special needs, they offer insights into similar challenges which helped us formulate a module to map healthy user input into a "simulated" user with physical challenges.

2.4 User-Centered Design and Co-Design

Sanders and Stappers refer to co-design as "the creativity of designers and people not trained in design working together in the design development process" [71], which is a very broad term that covers any activity that allows end users to influence the design process. They categorize the roles that users can take in this process into different levels of creativity that are motivated by their needs, level of expertise and amount of interest; this can include "doing" motivated by getting productivity, "adapting" motivated by appropriation, "making" motivated by asserting their own abilities, or "creating" motivated by getting inspired and expressing their creativity. [71]

Traditionally, user-centered design was approached from an expert perspective in which researchers would collect data by observing users (in a passive role) and bringing forward theories from other experts to develop knowledge. Whereas the co-design approach acknowledges people as "experts of their own experiences", and enables researchers to facilitate the inquiry by supporting the ideation and expressions of the users. [71]

Over the last decades, the process of co-design has gained momentum in the design space and has shown numerous benefits. [72]. However, prior work suggests that users often have difficulty explaining what features and functions they need or want in a new technological artifact [73]. Scholars posit interviews to be a good medium for collecting valuable information about the context of interaction and its constraints, that may not be available through passive observations only. [71, 74]

This project was originally planned with an emphasis on co-designing using focus groups, but due to COVID restrictions on in-person interactions, I had to adapt and shift towards the user-centered approach; utilizing online interviews as means for obtaining feedback from children and their parents. This project utilized user-centered design for the robot's basic functionality and operation and made use of discussions for the robot's interface for teleoperation (ex: joystick, touch, gesture control etc.). Although a proper co-design study with our target population during Covid-19 was not feasible, I attempted to include elements of co-design in the process. With reference to the roles proposed by Sanders and Stappers, children and parents took the role of "adapting" while the researcher guided their ideation process through the study.

Chapter 3

The Robot

The motivating question for this chapter is RQ1:

How can we exploit robots to create joyful play sessions that facilitate human connection for children with different levels of physical abilities and needs?

This chapter outlines the development process of MyJay and discusses technical design details as well as justification for some design choices made in the process. To help answer RQ1, some recommendations on designing robots for accessible play scenarios are presented in 3.5 [1].

3.1 Development Process

Initially I hoped to involve children in the design process via in-person sessions in the lab and in schools that include typically developing children and children with special needs in their educational activities, but due to the COVID-19 pandemic, I had to switch to an online setting. To overcome communication challenges introduced by online interviews, I used the robot prototype constructed after therapist feedback to initiate discussion in an online study. The online study is discussed in more detail in the next chapter.

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[1] This is a supplementary video for the chapter :`https://www.youtube.com/watch?v=8zjnKOeGBUc`

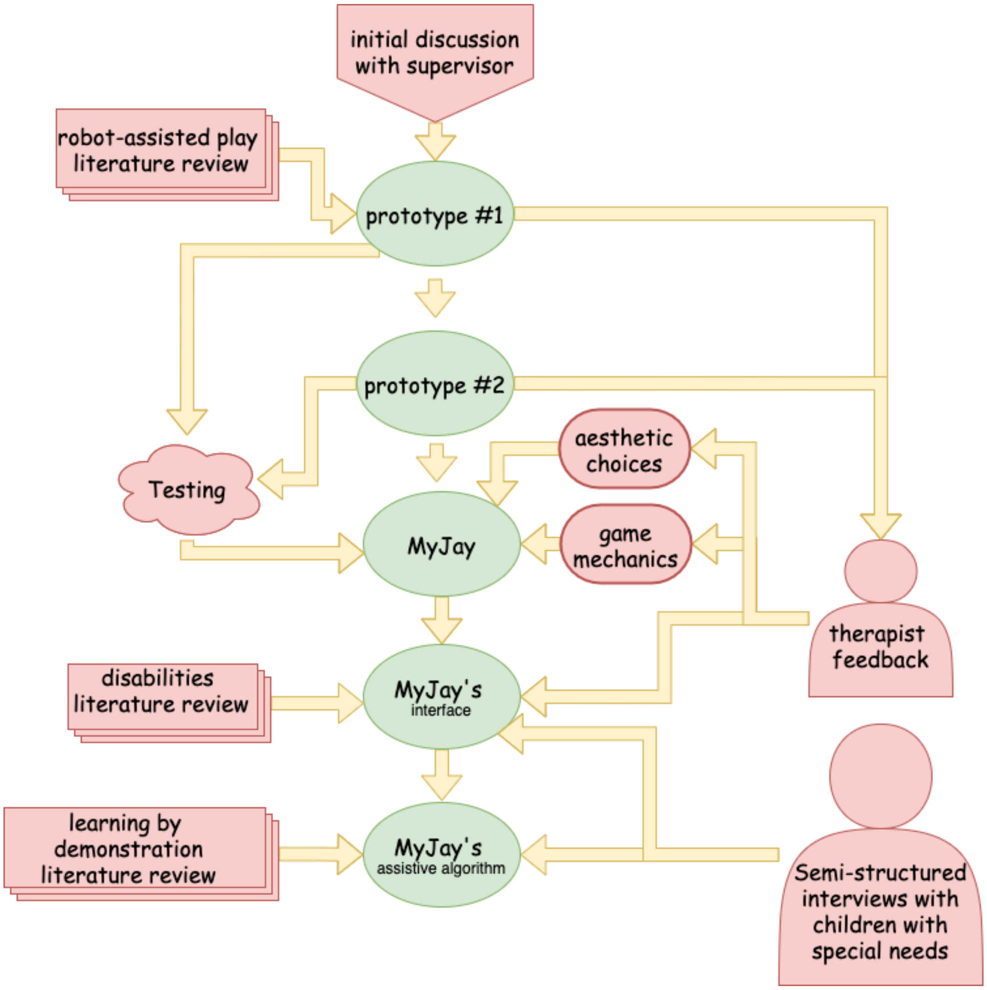

Figure 3.1: Different stages of development of the robot MyJay and the main factors influencing design choices at each stage

3.1.1 Identifying the Game and Robot Design

I aimed to design with target users rather than designing for them. This is especially important because designing play activities is not as simple as setting constraints and designing around them. Kristensson & Magnusson found that end-user ideas are more innovative and can match their needs better than the ideas generated by professional designers, whereas the the expert designers are able to create technically feasible designs that are more pragmatic [75]. As such, I did initial prototyping before engaging in participatory design in order to ground users' expectations, scaffold their ideation, and deal with limitations introduced by the COVID-19 pandemic in 2020.

Children are often engaged in play through the medium of games. When consulting a children's special needs expert, it was apparent that most children with motor-related special-needs often use screen-based entertainment. Such activities lack the spatial sense of the real world and are often done in solitude. Our goal was to create a game that allows children - especially those with upper-body gross and fine motor impairments - to compete and collaborate through a challenge that uses a robot they control. Inspired by the FIRST Robotics challenges made for student design teams [2], the idea of a field-based game centered around robots scoring through collaborative and competitive efforts helped formulate this project. The game elements handled by the robot are 101.6 mm diameter foam balls similar to balls used in beginner tennis practice. Balls were chosen as they are universal across cultures and used in numerous sports making it an intuitive object to interact with [76].

3.2 Game Concept

The concept of the game is an enclosed area where the robot collects balls, navigates around obstacles and shoots balls in a basket or an opening in the field wall as shown in Fig. 3.2. In the collaboration condition, children may work together controlling a single robot to achieve the game objective. In the competitive condition, two robots are influenced/controlled by different children, competing to achieve the game objective first. Both game modes aim to foster communication and play between children as well as conflict management skills and generally to provide a fun time. While solitary play is possible, and could be beneficial in terms of improving spatial awareness, it is not the main intended outcome of this design. The robot was designed around the game concept with ease of use, accessibility, child-friendly aesthetics and reliability as guiding principles.

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[2] https://www.firstroboticscanada.org/

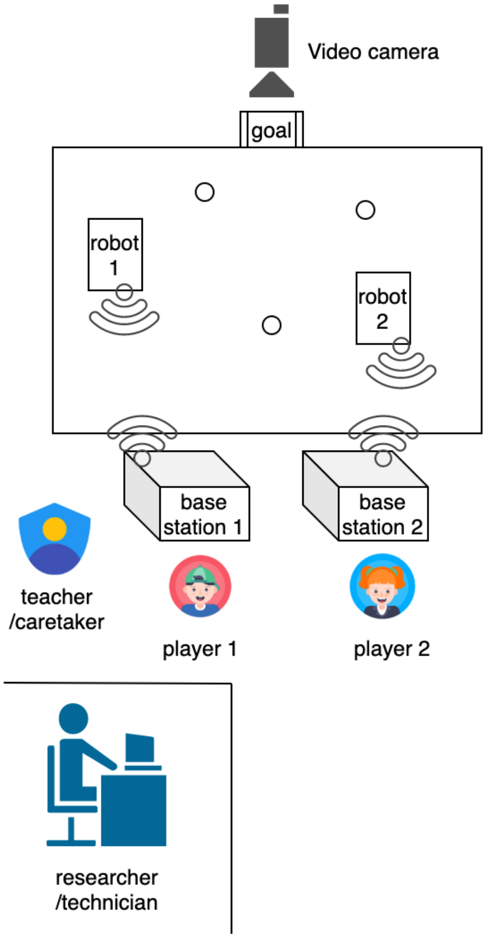


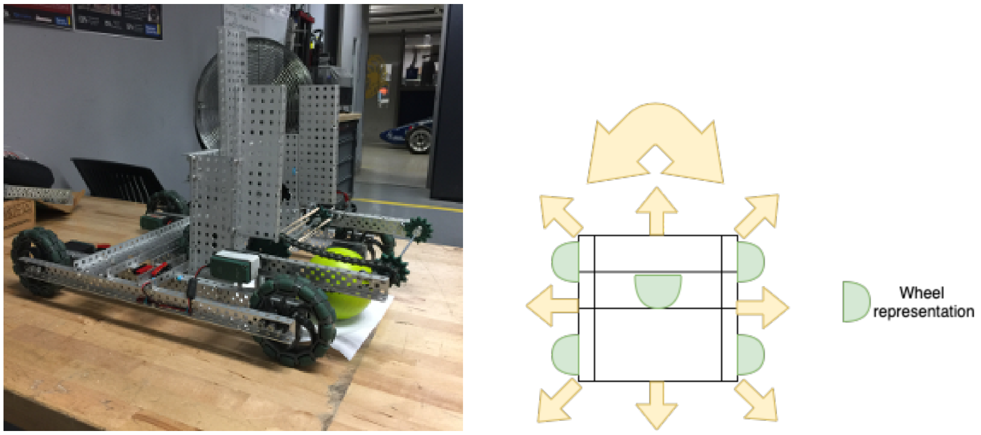
Figure 3.2: Schematic drawing showing proposed experimental setup.The robots are scaled correctly to the arena

Table 3.1: Outline play scenario inspired by robins et al. [1]

Actors/Roles	Two players are involved in the game. They could be children or a child with an adult/caretaker. All players have equal roles to guide the robot
Play Type	Sensory motor play, games with rules
Activity Description	The game consists of collaborative or competitive game play with two mobile robots. Players guide the semi-autonomous robots to pickup a ball, go to a scoring position and shoot the ball. The objective of the game is to create a fun and exciting scenario by having players control robots and assist them in scoring goals. Additionally, the game is meant to erase barriers of play due to varying physical abilities by having standardized autonomous behaviours with simple inputs from players. The motivations of child are: (1) the 'cause and effect' satisfaction. When a command is issued, the robot moves/shoots, (2) the excitement of anticipation - will the ball be scored, and (3) engaging in a game with peers/adults. The motivation of an adult is to build a nurturing relationship with the child they are taking care of, by playing exciting games with them.
Activity Model	Sitting on chairs at the base station, players issue commands using buttons/joysticks (or using other inputs). The robots receive a command to search for a ball and intake it. Robots acquire a ball and await the command to go to a scoring position. If the player issues the command, the robot aims at the goal using its vision sensor. Finally, if the player issues a command for shooting, the ball is thrust towards the goal which could result in scoring. Players may not get in contact with robots.
Place/Setting	The game requires a large empty room to setup the arena and basestations.
Artifacts/Media	A mobile robot that can intake a ball and shoot it is used. Some lights/sounds are added for celebration/dancing.
Time	The game ends when a score or time limit is reached.
Keywords	Ball game, enjoyment and excitement, social interaction, cause and effect, collaborative play, competitive play

3.3 Robot Concepts

For the robot core design, I decided to add a mechanism to pick up balls off the floor and throw/shoot them in a basket. With this basic concept in mind, two low fidelity prototypes shown in Fig. 3.3 and Fig. 3.4 were constructed to showcase the core game-play mechanics. The prototypes were constructed out of pre-drilled aluminum C-channels which sped up the process and allowed for easy and quick modifications for iterating. These prototypes were used to consult local therapists who provided very useful feedback which we used to construct a prototype of the current version of robot. This feedback drove the use of colors, lighting (on-robot LEDs) and the overall shape of the shell.



(a) (b)

Figure 3.3: (a) Low fidelity prototype #1 which is one of the prototypes used to initiate discussion with therapists. (b) H-Drive drivetrain design concept. This configuration allows the base to move in an holonomic fashion, meaning the robot can move in any direction depending on the output of each wheel. For example, the robot is able to strafe sideways, go diagonally and move like a normal differential drive robot. The motion is enabled by the use of omni-directional wheels

Prototype #1 was essential in understanding the engineering challenges/requirements for making a robot-assisted ball game. It featured a drivetrain with holonomic constraints and utilized a high speed flywheel (1̃0000 rpm) to shoot the balls. Due to the use of thin aluminum C-channels, the robot was lightweight and can be transported easily. Despite being very successful at achieving the desired task, this prototype was very loud due to the high speed flywheel and was unpleasant to use due to the emanated noise.

To address the constant noise issue with prototype #1, I constructed prototype #2,

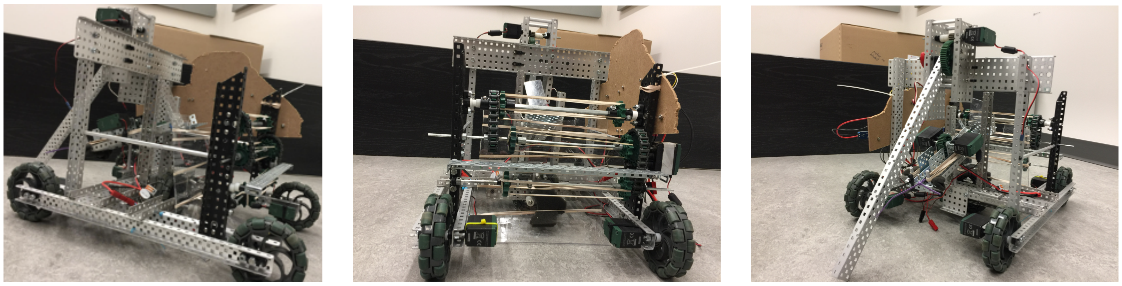
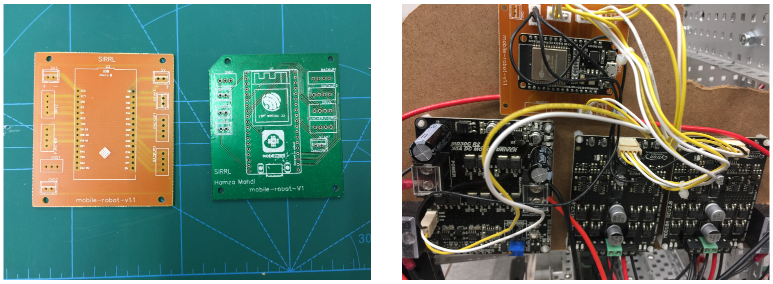

(a) (b) (c)

Figure 3.4: Low fidelity prototype #2 which is one of the prototypes used to initiate discussion with therapists. The figures showcase the robot from different sides.

which kept the same drivetrain concept but improved on the first prototype by using an elastic mechanism to shoot balls instead of a flywheel. The mechanism was much quieter, however, after winding the elastics back and releasing the latch to shoot the ball, the mechanism hits a stopper which results in a sudden impact sound. The sudden impact sound was much less desired than a constant noise as explained by a therapist at KidsAbility[3]



(a) (b)

Figure 3.5: (a) Printed Circuit Board (PCB) prototype. The initial design (right) and the revised one (left) are shown. (b) PCB mounted on the robot. A development ESP32 board was used and could be swapped easily in case of a malfunction.

For electronics, each robot was designed to act as a WiFi hotspot that accepts a standardized UDP message. This allowed them to accept messages from different sources on the network (joystick, co-proccessor on the robot), and act on each message based on its

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[3] https://www.kidsability.ca/

standardized tag. The prototypes were driven by an ESP32 microcontroller [4] which has built in WiFi and Bluetooth which makes it versatile and suitable for wireless data transfer. A cheap, custom circuit board (shown in Fig. 3.5) was designed for reliability of signal transfer between the microcontroller and motor controllers. There were no sensors used on the prototypes as the intention was to understand the mechanical requirements/potential challenges of building a child-friendly system.

3.4 MyJay's Design

After prototyping two robots and consulting therapists, we were ready to build a high quality "prototype". The design turned out to be reliable and attractive, and thus, this was kept as the final design and was improved incrementally over the past year.

MyJay's features are centered around maneuverability, collecting and "shooting" game pieces. Since this robot is designed to ultimately be open source, minimizing the number of pieces and the difficulty of assembly are priorities. As this robot is driven by children, it may collide with several objects on the game field, thus, robustness and reliability are also key. Most importantly, the robot has to be safe; although balls being shot are made of foam, energy used by mechanisms to shoot the balls could cause harm if designed incorrectly. MyJay was designed to have rigid mechanisms that rotate in place with little to no vibrations. A shell was also designed to enclose most of the robot's mechanical workings as an added precaution. The robot was first conceptualized using Solidworks. This allowed all parts to be assembled and tested for compatibility. 3D printing was used to create custom components and all other parts, including aluminum blocks for the frame, were sourced from sites available to the general public. Along with the shell, MyJay is about 570 x 330 x 525 mm in terms of dimensions.

3.4.1 Drivetrain Mechanism

Children with physical special needs, especially those with a lack of upper body fine and gross motor skills, may be unable to control and adjust a simple tank-drive robot due to the multi-step alignment procedures it requires. A swerve-based robot [77] with independently spinning wheels would be resource-intensive and too complex for potential users to build. The drive train used on MyJay is a mecanum wheel drive train [78]. This wheel type features small, diagonally aligned rollers along the perimeter of each main wheel, making

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[4] https://www.espressif.com/en/products/socs/esp32

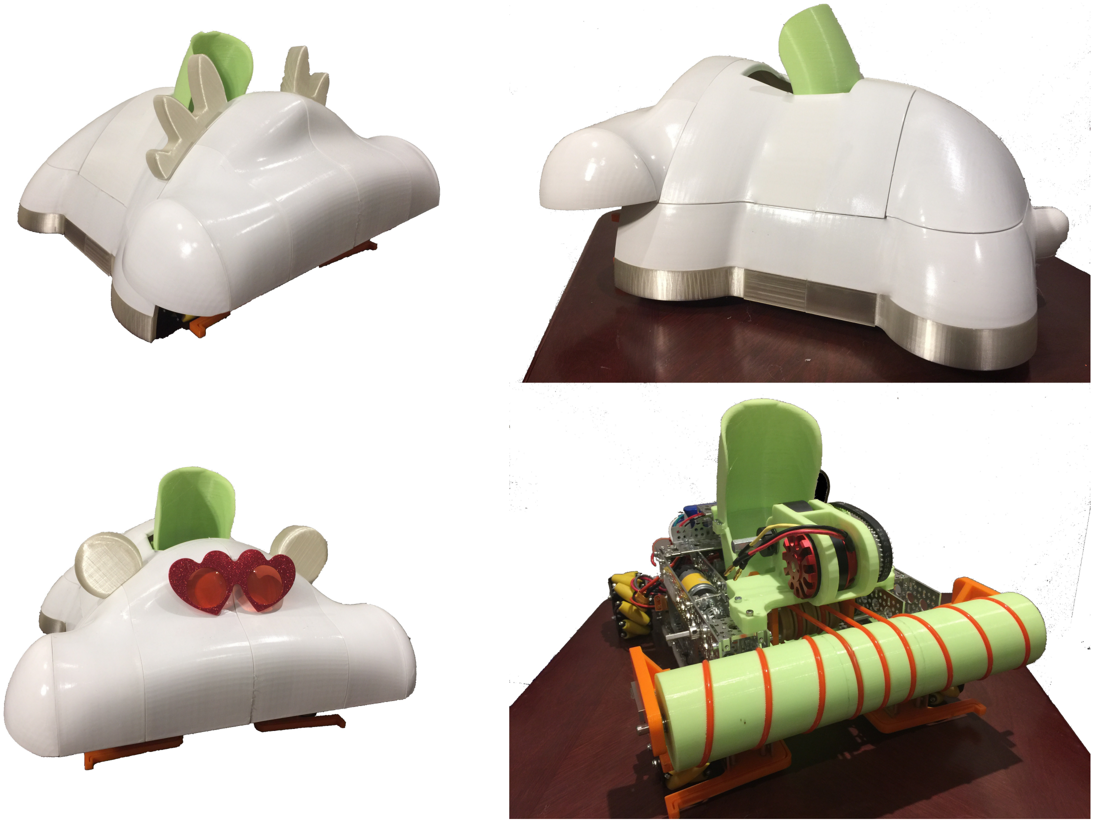

Figure 3.6: Examples of MyJay's shell configurations. The robot will typically be covered by the shell when interacting with children. The robot without its shell is shown in the bottom right. The shell was designed to be modular and accepts a wide range of accessories to suit different age ranges, as seen in the left images. Note: the current shell design includes holes for screw mounting unlike the seamless older version shown in this figure.

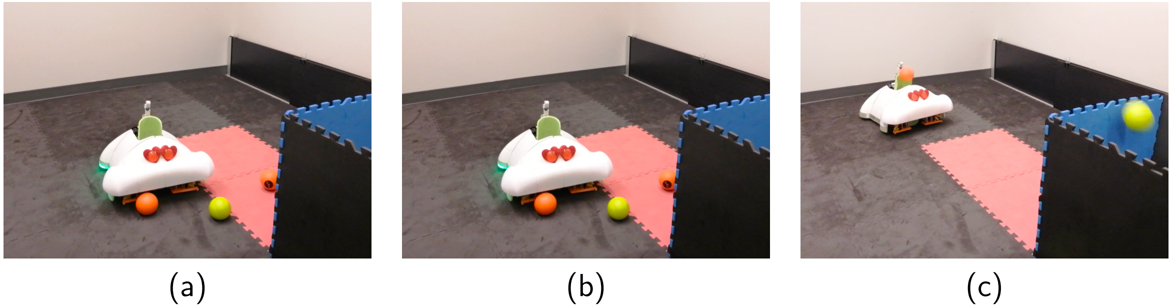
(a) (b) (c)

Figure 3.7: Sample scenario where the robot (a) identifies balls on the field, (b) picks up the balls and (c) throws them in a goal. Green lights can bee seen in (b) during robot operation indicating motion in the forward direction

it a holonomic drivetrain and enabling the robot to strafe in any direction. A commercially available mecanum drive train was purchased and altered to a rectangular configuration rather than the conventional square configuration to reduce the robot's volume. The final structure of the drive train and frame structure can be seen in Fig. 3.11.

Drivetrain Kinematics

MyJay's drivetrain is a single rigid-body chassis with a configuration $T_{sb} \in SE(2)$ meaning the robot can move in any direction x-y on a flat plane, and can rotate about the axis perpendicular to the plane. The chassis fixed frame b is relative to the fixed space frame s and T_{sb} can be represented by three variables $q = (\phi, x, y)$. The velocity of the chassis can be calculated by taking the time derivative of q.

The details of the derivation of kinematics are already well explored and beyond the score of this thesis. Some important equations are presented here for the sake of completion. A more detailed look at the kinematics of a holonomic drivetrain with mecanum wheels can be found in [79], which is where the kinematics of MyJay are drawn from.

As the rollers on the wheels are angled at 45 degrees, we have to create a mapping between the wheel driving velocity u and the chassis velocity $\dot{q}$. The matrix $H(\phi)$ (constructed by stacking the mappings between each wheel the robot h_i) creates the desired mapping as shown in equation 3.1. Please refer to Fig. 3.9 for illustrations of each symbol:

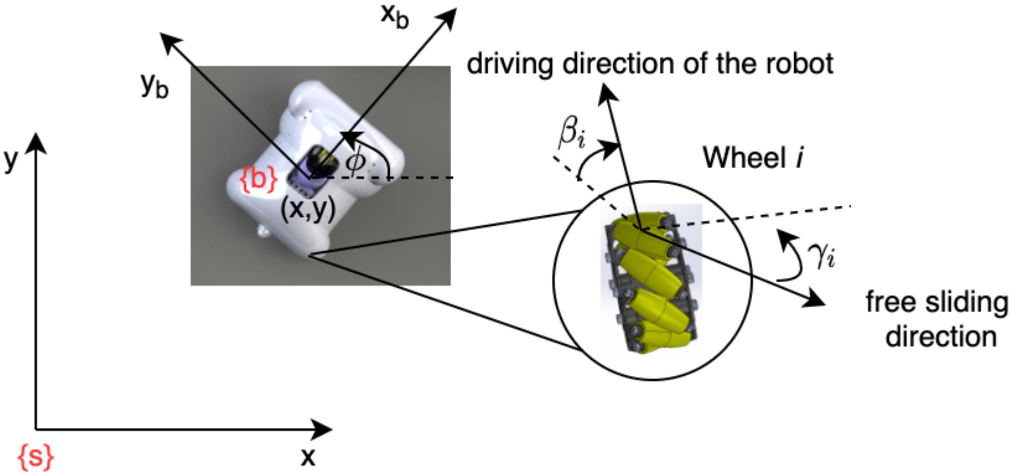

Figure 3.8: The reference frame {s} and the robot/chassis frame {b} as well as an illustration of one of the four mecanum wheels on the drivetrain.

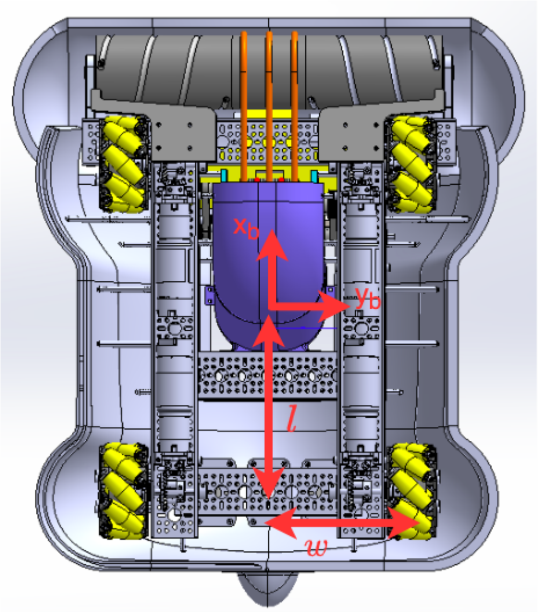

Figure 3.9: Kinematic model of MyJay's drivetrain. The driving direction of each mecanum wheel is $\beta_i = 0$. Please note this is a bottom view of the robot, captured in CAD software.

$$h_i(\phi) = \frac{1}{r_i \cos \gamma_i} \begin{bmatrix} x_i \sin(\beta_i + \gamma_i) - y_i \cos(\beta_i + \gamma_i) \\ \cos(\beta_i + \gamma_i + \phi) \\ \sin(\beta_i + \gamma_i + \phi) \end{bmatrix}^{\mathrm{T}} \tag{3.1}$$

where x_i and y_i are the positions of the wheel in the reference frame $\{\mathrm{s}\}$, and r_i is the radius of the wheel. Equation 3.2 shows how the matrix $H(\phi)$ can be used to map the robot's velocity to the wheel velocity.

$$u = H(\phi)\dot{q} = \begin{bmatrix} h_1(\phi) \\ h_2(\phi) \\ \vdots \\ h_m(\phi) \end{bmatrix} \begin{bmatrix} \dot{\phi} \\ \dot{x} \\ \dot{y} \end{bmatrix} \tag{3.2}$$

It is more convenient to avoid using orientation in the equation. The body twist $\mathcal{V}_b$ allows us to void using the orientation ϕ as shown in the equations below:

$$u = \begin{bmatrix} u_1 \\ u_2 \\ u_3 \\ u_4 \end{bmatrix} = H(0)\mathcal{V}_b = \frac{1}{r} \begin{bmatrix} -\ell - w & 1 & -1 \\ \ell + w & 1 & 1 \\ \ell + w & 1 & -1 \\ -\ell - w & 1 & 1 \end{bmatrix} \begin{bmatrix} \omega_{bz} \\ v_{bx} \\ v_{by} \end{bmatrix} \tag{3.3}$$

Where the body twist is defined as:

$$\mathcal{V}_b = \begin{bmatrix} \omega_{bz} \\ v_{bx} \\ v_{by} \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\phi & \sin\phi \\ 0 & -\sin\phi & \cos\phi \end{bmatrix} \begin{bmatrix} \dot{\phi} \\ \dot{x} \\ \dot{y} \end{bmatrix} \tag{3.4}$$

3.4.2 Intake and Elevator Mechanisms

The intake and elevator mechanisms are responsible for collecting the balls and storing them in the robot to be shot later. The intake and elevator motors are stored inline with the C channels on the frame near the top of the robot and motion is transferred from the motors using beveled gears. This allows for a more compact mounting of the motors, which in turn, gives the designer more freedom in terms of shell designs. Polycord, a plastic polymer solid cord, doubles as transmission and a friction material to draw the balls into the robot. A timing belt and pulleys were used to translate the rotation of the motor shafts

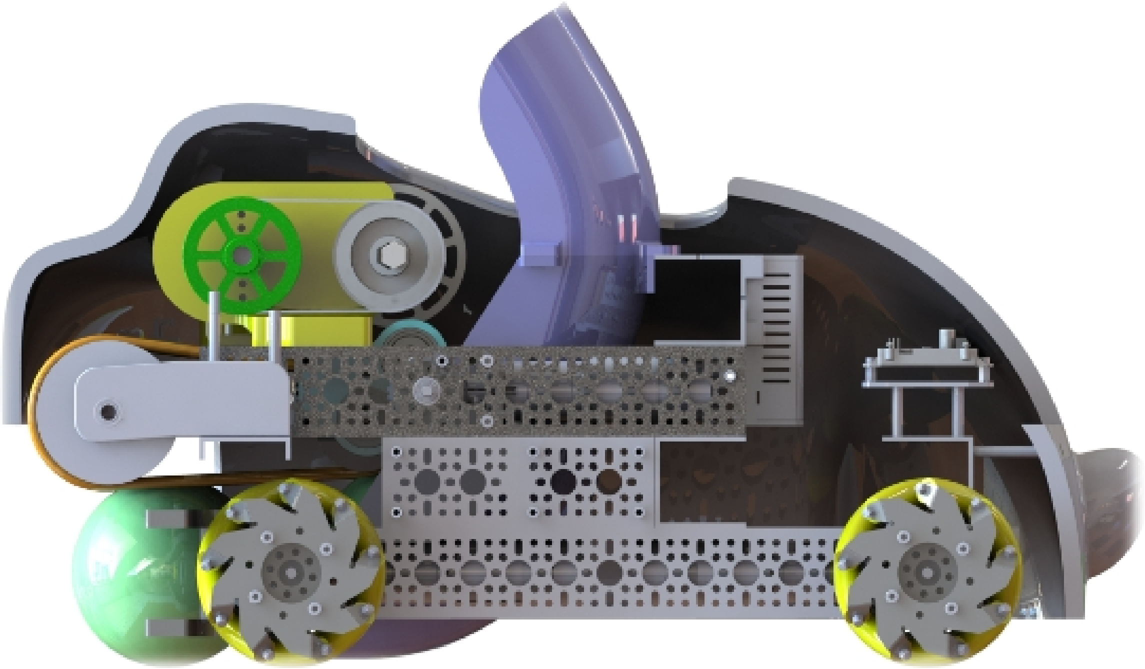

Figure 3.10: Side profile of MyJay's intake, elevator and flywheel mechanisms

to hex shafts with two layers of rollers connected via polycord belting. The rollers were 3D printed to be force-fit onto their shafts, with bearings for reduction of friction. This assembly was secured using two 3D printed brackets, shown in Fig. 3.11 (Cyan color). The intake of the robot was also 3D printed; it features two spiraling polycord-lined grooves with a wave pattern that propagates to the center of the robot when spinning clockwise. The elevator was 3D printed to an optimal curve that ensures the game piece maintains constant contact with all belting.

3.4.3 Flywheel Mechanism

This mechanism is mounted atop the elevator. A brushless DC motor spins a timing belt and pulleys connected to a compliant rubber wheel revolving at $\tilde{3}000$ rpm to launch the ball in a pre-defined arc path. The bracket holding the mechanism together, seen in Fig. 3.11 in yellow, was 3D printed with an additional motor guard for added safety.

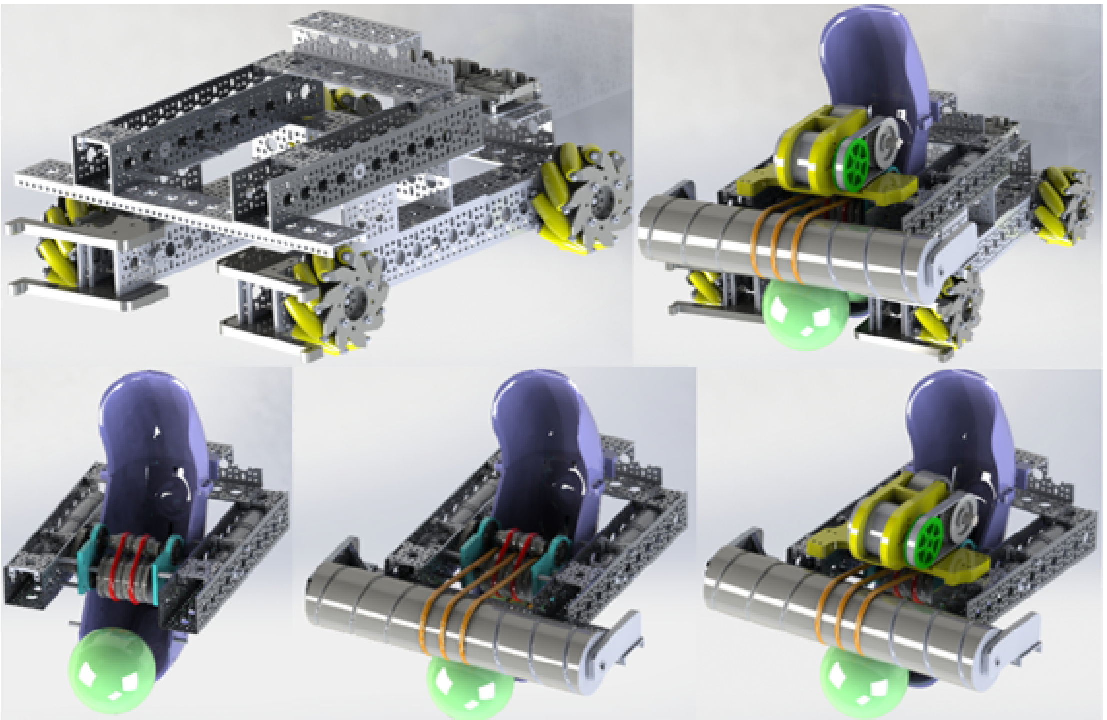

Figure 3.11: Mechanisms rendered in Solidworks: drive train and frame (top left), elevator (bottom left), intake (bottom middle), flywheel (bottom right) and full robot (top right)

3.4.4 Electrical System

The electrical system was designed using widely used, commercially available parts. Fig. 3.12 describes the electrical system. The system was designed/programmed with modularity as a central theme. For example, the Jetson Nano can be replaced with any generic system on chip (SoC) device such as the Raspberry Pi [5]. The system can be directly teleoperated over WIFI from any device sending standardized messages using UDP. All documented code will be made publicly available once this robot design project is finalized.

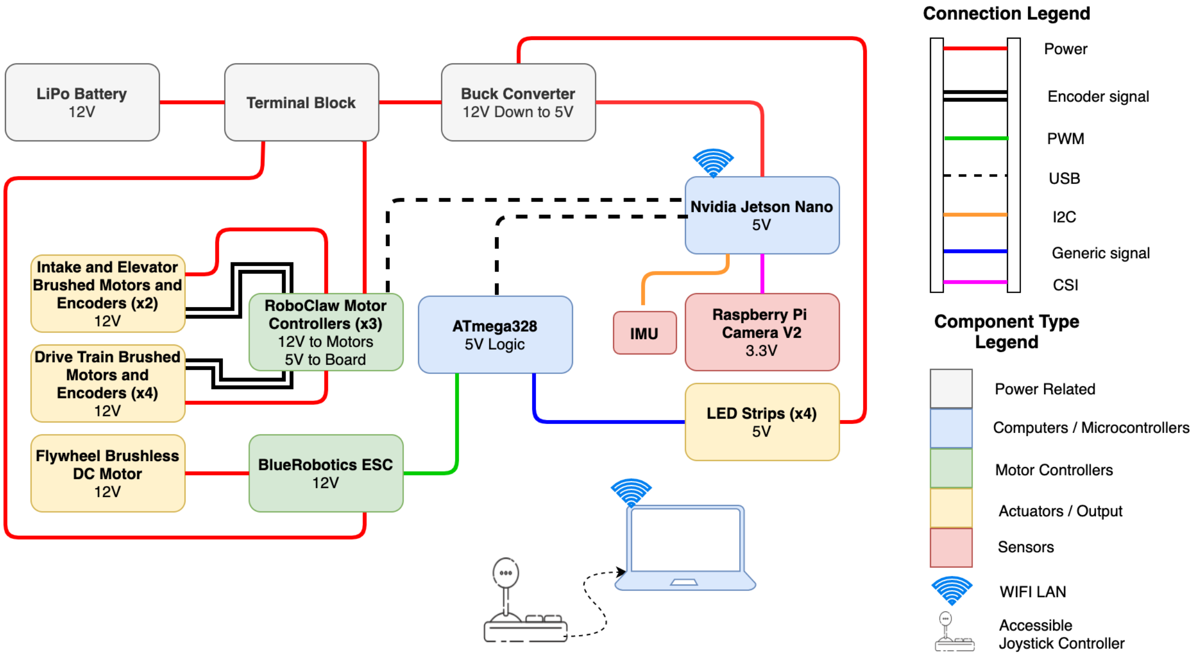

Figure 3.12: System architecture: power and logic levels are shown

The robot runs on a 3 cell Lithium Polymer (LiPo) battery with a voltage of 1̃2V. The battery was chosen so that motors can be fed power directly from the battery without any DC-DC voltage level shift. As for the logic system, a generic DC-DC buck converter shifts the voltage down to 5V. The Nvidia Jetson Nano SoC [6] is the main on-board computer which takes care of perception, autonomy, motor operations, networking and data collec-

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[5] https://www.raspberrypi.org/

[6] https://www.nvidia.com/en-us/autonomous-machines/embedded-systems/jetson-nano/


(a) (b)

Figure 3.13: MyJay using vision to navigate autonomously to a ball. (a) Field view, and (b) on-robot view.

tion. It communicates with 3 RoboClaw motor controllers [7] over USB. It also uses USB to communicate with the Arduino Nano microcontroller [8] which is responsible for controlling the robot LEDs and the brushless flywheel motor driver. The Jetson development board exposes a number of pins such as (1) I2C which is used to communicate with an MPU6050 Intertial Measurement Unit (IMU) [9], and (2) CSI which is used to communicate with a raspberry pi camera [10].

3.4.5 Semi-autonomy and Teleoperation

MyJay is semi-autonomous by design to allow children to be part of the game regardless of their ability to control it; the level of autonomy can be adjusted depending on the user. The initial plan was to have discrete levels of autonomy and change the settings before starting a play session. However, I decided to use a machine learning model (discussed in 5, which allows for estimation of the user's "need" for assistance in a continuous manner. The robot is equipped with a camera as its main sensor for perception. Since the robot is placed in a specific starting point on the field, odometry from drivetrain encoders are used to localize the robot. An IMU is used to determine the robot's orientation/angular velocity.

The robot's camera is used to track balls and identify their positions relative to the

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[7] https://www.basicmicro.com/Roboclaw-2x7A-Motor-Controller_p_55.html

[8] https://store.arduino.cc/usa/arduino-nano

[9] https://invensense.tdk.com/products/motion-tracking/6-axis/mpu-6050/

[10] https://www.raspberrypi.org/products/camera-module-v2/

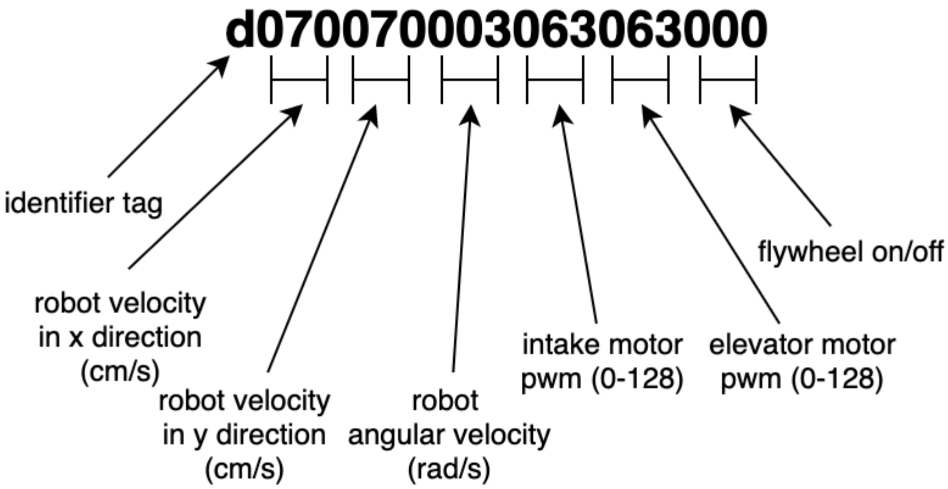

Figure 3.14: Example teleoperation message sent over UDP. Please note that velocities (x,y and angular) are shifted so that the numbers shown are for zero velocity, and 000 would mean a maximum negative velocity.

center of the robot. I opted for classical image filtering techniques rather than using machine learning models such as convolutional neural networks (CNN). For basic autonomy cases, a simple PID feedback loop [11] is used to steer and move the robot towards a detected ball as shown in Fig. 3.13.

Aside from partial autonomy, two users may collaborate to influence/control the robot's actions simultaneously. This could between parents/carers and children or between children. For example, one user could control the motion of the robot and another user could control the collection of balls/shooting. This shared autonomy scheme may increase the accessibility of the robot and help build social connections between users by having them collaborate on a fun task. In-person studies need to be performed in order to check the validity of the aforementioned claim.

UDP Teleoperation

Teleoperating over a local network needs to work regardless of the operating system on the base-station machine where the joystick is connected. Instead of using ROS (see subsection 3.4.6), I send UDP packets over the local network on a specified port. Once a message

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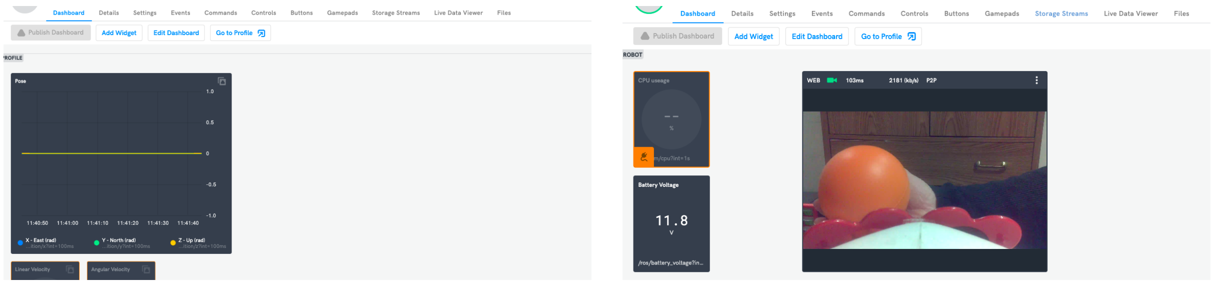
[11] https://www.ni.com/en-ca/innovations/white-papers/06/pid-theory-explained.html



(a) (b)

Figure 3.15: Screenshots of the ROCOS online platform for robot status monitoring. (a) Odometry tracking widget, and (b) robot status and on-board camera stream via peer to peer (P2P) streaming.

is recieved on the robot, it is translated to a standard ROS Twist message and published over the *cmd_vel* topic.

Fig. 3.14 shows how a UDP message for teleoperating MyJay is structured. The first character is an identifier tag for future use in case multiple messages of different kinds are being sent to the robot. As for the rest of the message, each 3 characters can be used according to the programmer's needs. For example, the current standard can take a number between 000 and 999. This format was chosen for modularity and ease of use. The advantage of this format is anyone can send teleoperation commands to the robot from any device as long as the correct IP address and the correct networking ports are selected.

Internet Teleoperation

I created a remote teleoperation system which would allow users to control the robot over the internet. I used the Google Firebase [12] real-time database as it allows for sustained transfer rates of up to 10MB/s. The message format was kept the same as the UDP messages discussion earlier for ease of use.

Aside from Firebase, I tried ROCOS [13], which is a cloud platform to build and manage your robot operations. ROCOS is typically used for industrial purposes, but its ability to connect to on-robot ROS systems natively gives it an advantage as it requires little work to setup robot teleoperation from the web browser. Their dashboard allowed for camera

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[12] https://firebase.google.com/

[13] https://www.rocos.io/

Figure 3.16: Screenshot of the teleoperation user-interface on the ROCOS platform. Aside from recieving inputs from joysticks, the webpage allows for custom buttons and commands. The robot can be visualized, and its position on the virtual map is updated based on odometry messages. The on-robot front facing camera feed can be seen on the right side.

viewing, monitoring robot status and sensors (see Fig. 3.15) as well as visualization of the robot in a virtual environment as shown in Fig. 3.16.

This was initially intended to be used in remote studies with children with special needs. However, we would have still had to send the joystick controllers by mail which has risk of breaking during shipping, and introduces logistic limitations such as having to buy many controllers. Additionally, it would require parents to have some knowledge on how to setup the joysticks and connect to the database without the presence of a researcher. Finally, even if everything works smoothly with little delay, it is still a very different experience to teleoperate the robot remotely, and would not be conclusive for in-person interactions. Due to the aforementioned challenges, I did not go ahead with the remote experiment despite the fact I implemented the programs/overcame technology requirements. It would be interesting to create a reliable, user-friendly and accessible system for remote robot teleoperation but this project is outside the scope of this thesis.

3.4.6 ROS Support

In order to extend the shelf life of MyJay as a research robot, all on-board software interfaces with the Robot Operating System (ROS) [80]. ROS is widely used in research robots and enforces standardized data streaming between different programs (also known as nodes) on any local area network (LAN). Additionally, ROS comes with standardized

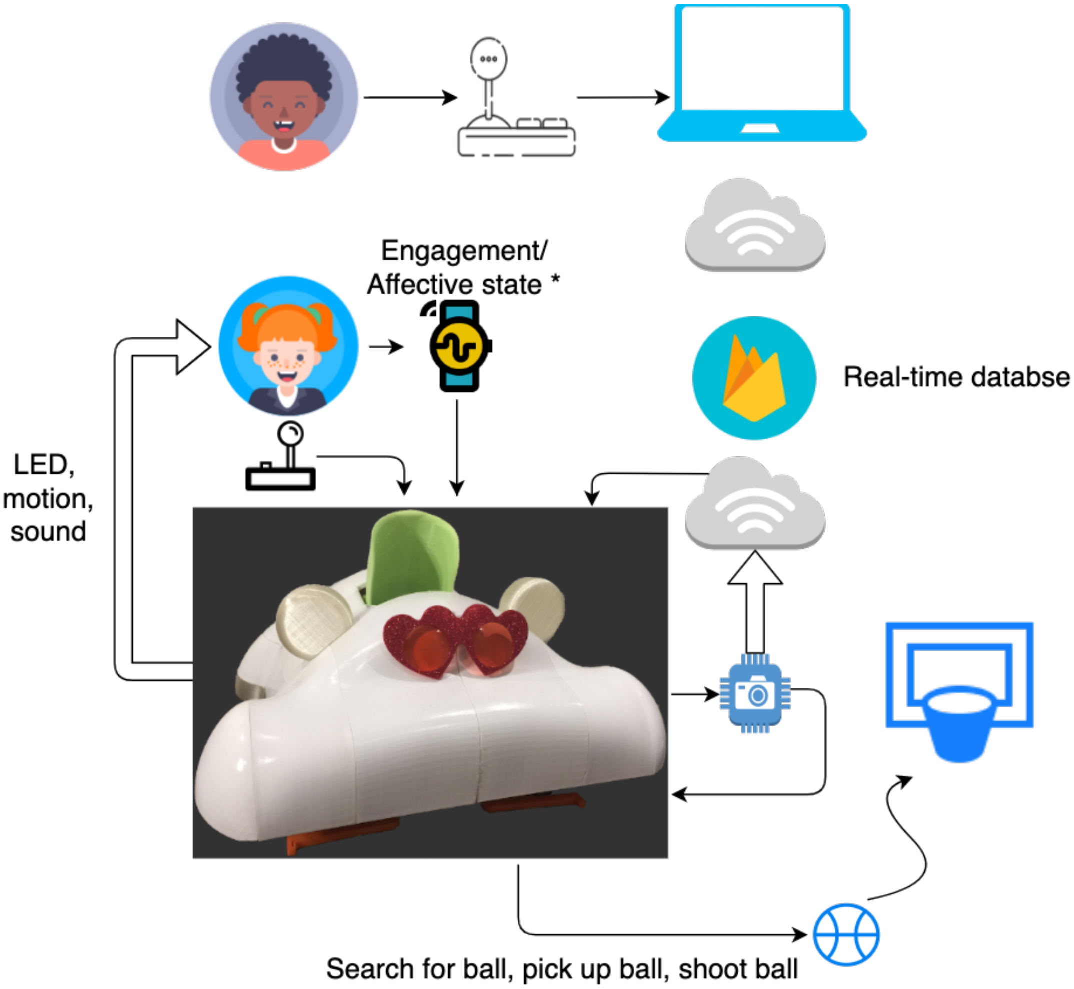

Figure 3.17: Proposed scenario for social-distanced and in-person interaction. MyJay can be teleoperated locally or over the internet. The vision system ensures ease of teleoperation by tracking the balls and allowing for automatic pickup, and by aiming the robot at the goal. * Engagement can be used as feedback and measured using a smart wearable (not implemented yet).

Table 3.2: ROS packages on MyJay

Package	**Description**
myjay_cameras	(1) starts raspberry pi camera feed, (2) tracks ball position relative to the robot based on the camera feed, and (3) streams a compressed video feed over the network.
myjay_core	This package is resonsible for just about every basic functionality: (1) communicate with the motor drivers and receive encoder data from them, (2) read IMU data, (3) robot localization and sensor fusion, (4) publishing robot link transforms, and (5) deciding what the LEDs show in terms of color and pattern. This is the package that recieves standardized ROS Twist messages and moves the robot based on the messages.
myjay_teleop	This package recieves joystick teleoperation commands and publishes them to ROS in the form of standardized Twist messages. There are multiple nodes that can be used here to: (1) receive commands over the internet using Google's Firebase realtime database, (2) recieve UDP messages over LAN, and (3) distort teleoperation messages (for the mobility challenge simulation experiment).
myjay_executive	This package hosts state machines written using the SMACH library [81].

software packages that make data collection, visualization of robot states, and robot localization/navigation more easily accessible. Discussing the details of how ROS works is beyond the scope of this thesis. In order for MyJay to support ROS melodic [14], it runs on a Linux Ubuntu 18.04 operating system.

I have created a few packages to aid in the basic operation of MyJay (see Table 3.2). The goal is enable other researchers to easily use MyJay through modularity of software and standardized package structure. Each package contains multiple programs which can be launched as ROS nodes. Each node can receive and send multiple messages simultaneously. Fig. 3.18 shows the current system of nodes and the messages they send over the ROS system.

MyJay makes use of some open-source packages available with ROS such as *rosserial* and *robot_localization*. *rosserial* allows for communication between ROS and external microcontrollers over serial connections, which simplifies and standardizes message definitions

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[14] http://wiki.ros.org/melodic

if extra microcontrollers are needed. *robot_localization* allows the use of encoder odometry and IMU data to estimate the robot's states through an extended kalman filter [82].

Emphasis was placed on compact software design. For example, the *myjay_driver* node performs a few functions that could have been spread across multiple nodes such as multiplexing velocity commands, commanding motors, and calculating odometry from encoder readings. Another example is the minimalistic transform tree which defines offsets between robot links and between the robot and the map frames. As per REP-105[15], I followed a standard for naming conventions for coordinate frames of mobile platforms used with ROS. A transform tree of MyJay links is shown in Fig. 3.19.

3.4.7 Interaction Elements

Shell Design

Children learn and interact with objects through their senses. Their initial interest in physical objects is often attained through visual stimuli [83]. Thus, creating a shell for MyJay would double in function to assist in safely covering moving mechanisms and to be an aesthetically appealing characteristic. Children have an orientation towards the natural through the "Biophilia Hypothesis"; it describes that this attraction has developed as humans evolved [84]. If one is to examine the main characters of children's television shows, movies and toy franchises, animals are often chosen. Tame and socialized creatures [85] in popular culture roles were found to be central to the plot almost half the time [86]. A study investigating the favourite animals of children from various backgrounds found that the most preferred species were the dog, cat, squirrel, horse and swan [87] with all other quartiles featuring mainly four-legged animals. Such animals are also commonly used in animal therapy [88]; robots modeled after these therapy animals often invoke the same positive reaction from humans [89]. The following design criteria was determined for the robot shell:

- Moving mechanical elements of the robot should be hidden by the shell
- The shell should aim to have lateral symmetry with mainly organic curves
- Orientation of the robot should be obvious from the shell body
- The shell should contrast the floor of the game field

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[15] https://www.ros.org/reps/rep-0105.html

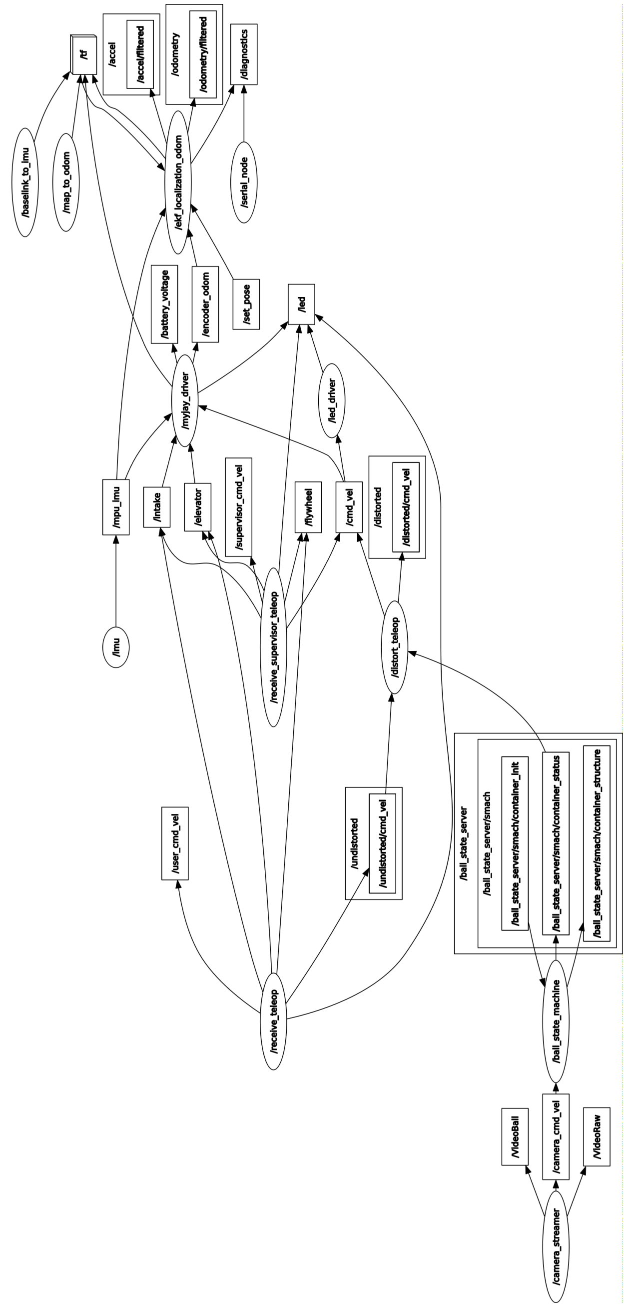


Figure 3.18: Diagram of the ROS system for MyJay. Ovals represent nodes and rectangles represent topics which relay messages between nodes.

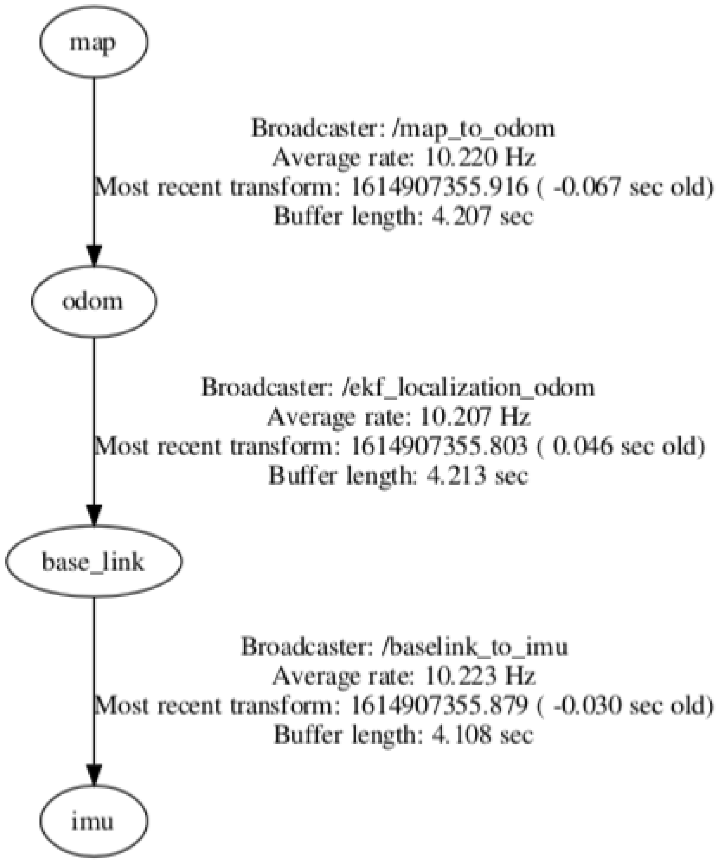


Figure 3.19: Graphical representation of the transform tree between coordinate frames in MyJay along with the average frequency at which the broadcaster sent out the corresponding transform.

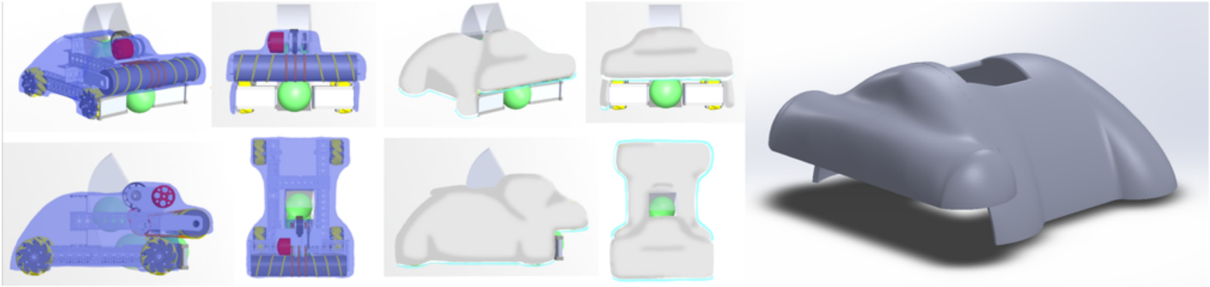


Figure 3.20: Shell development process: preliminary shape sketch (left), rendered sketch (center), final shell with CAD (right)

- The robot's internal state can be communicated through the use of lights
- The shell should not use symbolism belonging to any gender
- The shell should take a zoomorphic, four-legged shape, but not imitate any existing animal species in order to avoid unrealistic expectations
- The shell should have multiple configurations to attract children with different ages and aesthetic preferences

Autodesk Sketchbook was used to draw transparent and opaque bodies to represent various shapes of the shell that satisfy the above conditions as shown in Fig. 3.20. Shapes that were impractical to fabricate and 3D print were then eliminated. The final shell shape was chosen as it could be created using the advanced surfacing and thickening commands in Solidworks. The final design features a high backed, four-legged body (Fig. 3.20 right).

As the shell is 3D printed, due to limitations in printer bed size, it was divided into several pieces with mutually perpendicular planes.

Light and Color

Another visual stimulus added was light through the use of multi-color LED strips in the base perimeter of the the robot and the accessory ears. This can be a method of feedback for the child [83] as they can see the result of their commands on the robot manifested in color changes. A study found that children associate motion verbs to point-light displays, suggesting that animated light can be an effective communication tool [90].

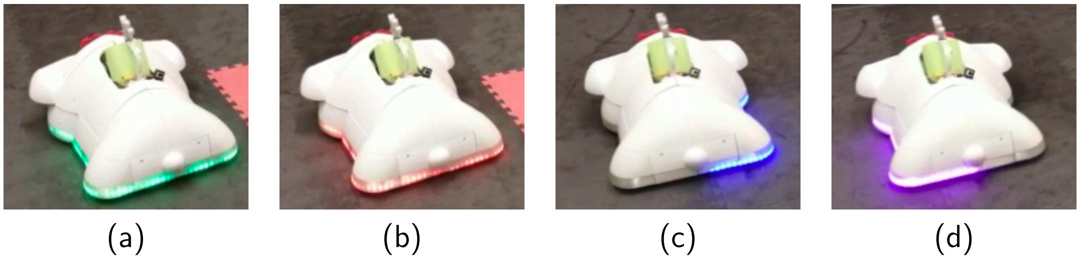


Figure 3.21: MyJay communicating its motion directions through light cues: (a) forward, (b) backward, (c) right, and (d) left.

As mentioned in the literature review section, lights have been used to implement *perceptual crossing* to enhance communication between the robot and the user [29]. An example of perceptual crossing in MyJay is when it perceives a ball, and moves towards it, emanating moving light patterns which vary in color based on its direction of motion.

The incorporation of light needed to be done safely as children can be very sensitive to light. In a study conducted with 27 children with epilepsy, it was found that certain light flash intensities and frequencies caused sensitivity or seizures. Mainly high intensity light at flash frequencies greater than 10Hz caused epileptic symptoms in the children. On some occasions, single flashes also caused children to become sensitive [91]. MyJay does not flash any lights, but rather fades from one colour to another quickly; this softens the effect of sharp colour transitions. Directional lighting is done through a propagating sign wave rather than a point flash moving along the LED strip. Other patterns include showing a single colour, a rainbow, and fading in and out. The rainbow light signal will be used as reward feedback to the child when they score or reach a point threshold.

Motion

The robot's holonomic drive-train allows it to convey a wide range of motions such as moving in an arc of arbitrary radius or moving towards a target position while spinning. This could be used to give the robot a "personality" such as 'dancing' after scoring a goal.

3.5 Lessons Learned

The current version of MyJay has been in development for more than 1 year; many decisions and design changes were made to make MyJay into a fully functioning robot. Though RQ1 requires in-person studies to be definitively answered, the following recommendations were formulated to help answer it:

Determine the Environment First: Understanding the context in which the robot operates accelerated the development process. By restricting the robot's operation to a highly controlled environment (i.e. a pre-determined playing field), I was able to produce two prototypes fairly quickly which allowed us to understand the problem better, narrow down which mechanisms to use, and made us aware of a few issues, the most important one being noise generated by the robot mechanisms. Having created two prototypes, we reached out to a local children accessibility organization and connected with an expert on children with special needs to consult them before creating the current version of MyJay. This helped in choosing the colors, lighting and the overall shape of the shell.

Importance of Modularity: As we intend to make MyJay open source once fully developed, heavy emphasis was placed on modifiability of parts. The aluminum parts making up the frame were chosen from a supplier that offers pre-drilled channels, with many places to mount external mechanisms. The intake and the elevator sections were specifically 3D printed so that using a ball with a different size would only require a minor redesign and reprint of these specific parts rather than redesign the entire robot.

Open-source Design Tips: Designing a truly open source robot can be difficult as small differences in part sourcing and in the manufacturing process can yield a very different robot that may not function consistently. Using pre-drilled aluminum channels reduces the variability that usually results from machining raw aluminum stock. Additionally, all custom parts not purchased from publicly available sources were designed to be 3D printed in order to avoid complex manufacturing steps and the need for a fully equipped machine shop. 3D printed parts were designed and segmented so that they fit most hobbyist level 3D printer beds.

Designing for Children: Children, specifically children with multiple special needs can be sensitive to sounds and light flashes. This makes designing mid size robots such as MyJay for children a difficult process. Many mechanism iterations were tested to balance robot reliability and robustness with silent mechanism operation. For example, I found that using relaxed pulleys, when possible, reduces noise even without the use of precision bearings.

Chapter 4

Target User Feedback

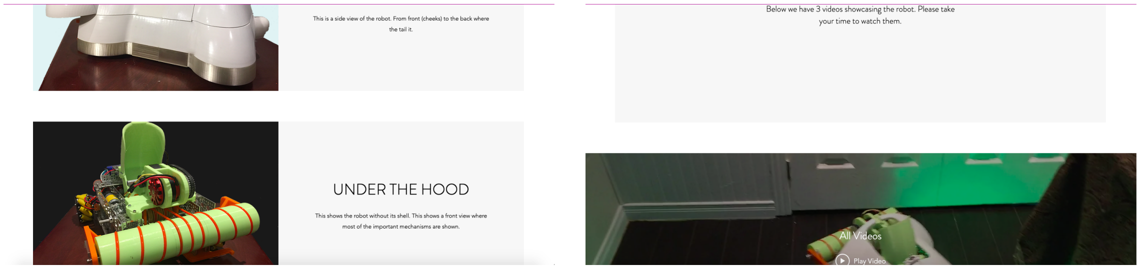
This chapter discusses an online study where intended users of the robot were shown pictures and videos of the robot and then interviewed to get feedback. The interviews were motivated by RQ2:

How can we involve children with physical special needs, specifically children with upper limb challenges, as part of the design process of inclusive robots for robot-assisted play?

Results of the user interviews are explored along with lessons learned about conducting such interviews and designing from feedback.

4.1 Motivation

As mentioned in the previous chapter, due to COVID-19, we could not hold in-person studies with the target users; children with special needs. To move from the low-fidelity prototypes to MyJay, we consulted therapists on children's preferences/needs. Once MyJay was constructed, we took photos and videos of the robot and used them to conduct the interviews. At this point, we were seeking design tweaks based on user needs and feedback rather than a full redesign of the robot. However, we avoided designing the user interface (i.e. how children control the robot) prior to this study as to give end users full opportunity to inform the design. The interface is arguably more difficult to design than the robot in terms of usability and having an intuitive interface would change the way children interact with the robot.


This is a side view of the robot. From front (cheeks) to the back where the tail it.

UNDER THE HOOD

This shows the robot without its shell. This shows a front view where most of the important mechanisms are shown.

Below we have 3 videos showcasing the robot. Please take your time to watch them.

(a) (b)

Figure 4.1: Screenshots of the website made for the study

In order to make the study feasible remotely, we uploaded the photos/videos of the robot and posted them on a website [1].

4.2 Methodology

4.2.1 Participants

A total of 9 families were recruited via Facebook groups for parents of children with special needs or via mailing lists of accessibility organizations. Numerous community-run Facebook groups and over 30 organizations were contacted, however, responses were limited due to reasons listed in discussion. The online nature of the study allowed us to contact organizations from all over North America, which resulted in a very diverse pool of participants despite limited participation. To focus the scope of the study, only families of children with upper limb challenges were recruited. Additionally, participation age was restricted to 6-12 years as this was the assumed target age group to use the robot based on therapists' feedback. Table 4.1 shows the demographics of each participant. Siblings were allowed to engage in the discussion if they were interested, especially since the robot design aims to be inclusive to all, and siblings might be the ones playing with a child with special needs in the first place. However, since the siblings did not have any physical challenges, they were not formally considered as study participants and no demographic information was collected from them. Finally, a parent or carer was required to participate in the interview as well to provide feedback and facilitate interviewing the children. This study received ethics approval from the University of Waterloo Office of Research Ethics.

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[1] `https://hamzamahdi96.wixsite.com/website`

Table 4.1: Description of participants

Child ID	Age	Gender	Physical challenge
1	6	F	Cerebral Palsy
2	6	M	Fine Motor Difficulties
3	7	M	Cerebral Palsy, Cortical Vision Impairment
4	6	F	Dravet Syndrome
5	6	M	Cerebral Palsy
6	11	M	Hemainopsia, Left Hemiparesis
7	12	F	Cerebral Palsy
8	12	M	Cerebral Palsy (Left Hemiplegia)
9	6	F	Cerebral Palsy, Epilepsy

4.2.2 Procedure

Interested parents completed an online sign up form which included study information and consent procedure. The form also collected basic information such as child age, medical condition and gender. Participants were instructed to go through the website before the interview. Interviews were conducted over the phone or using video conferencing programs and took 30-60 minutes. Children were required to give assent verbally before participating in the interview. A semi-structured interview format was used to get participants' input, opinions, and ideas. Questions and themes used in the interview are shown in Table 4.2. In addition, the researcher asked probing questions when appropriate to engage the participants in deeper discussions about the interface design. Audio was recorded and later transcribed for analysis.

4.2.3 Semi-Structured Interviews

Interviews involved a researcher asking families about their initial reactions based on their review of the website prior to the interview. They would express their impressions of the robot's general design, shape and functionality. The researcher would then clarify the intended use of the robot and how it is able to accomplish actions shown in the video. Additionally, context regarding game modes would be given to participants who would, in turn, provide suggestions on how the robot could be used in individual or group settings. Children in particular would be asked what they think of the robot's appearance and accessories, and what they think it represents (e.g. children typically thought it is

Table 4.2: Questions from the semi-structured interview protocol

Focus of Research	**Questions**
Robot Design	What do you think this robot is able to do? What do you think of the robot design? Of the different configurations in the photos, which is friendliest? What do you think the lights around the robot mean and how would you like to see colors change?
Game Setup	(After explaining the robot's purpose) Do you think this could be a fun activity? What do you think of the playing field concept shown on the website? Do you think the game would be enjoyable with one child controlling each robot, or two children controlling each robot?
Interactions with peers	What challenges do you have when you play with your friends? Do you think this robot can help create a game where you can play with others more?
Accessibility	Are you sensitive to bright light or color flashing? Do you have any concerns regarding the robot you saw on the website
Interfaces with Digital Media	How often do you play video games, If any what games specifically? How do you play these video games? What controller do you use?
Open Ended	Do you think a robot game has a place in your play activities? Do you have any improvements we can apply to this robot

mimicking an animal). Other questions included how the child deals with their condition and interacts with media such as video games or online schooling. They would also be asked how they prefer to control the robot with reference to what they have seen it do and what they already use to interact with digital media. This typically took the longest as participants were encouraged to suggest innovative ideas with the researcher commenting on the feasibility of each idea. Participants were also asked about lights emanating from the robot and what they thought of them. Some participants also discussed the potential benefits from using the robot, how it was made, or even how children play with their friends in general. Finally, participants were asked to suggest improvements or modifications for the robot.

4.2.4 Analysis

Given the qualitative nature of semi-structured interviews, thematic analysis was performed to identify any patterns or themes that emerged [92]. Otter AI [2] was used to transcribe audio into text data. Notes were taken during initial listening to the interview audio by two researchers. The researchers discussed their notes and keywords were identified. A quick pass through the transcribed text was done to correct any audio transcriptions and highlight keywords. A second detailed pass was performed to search for themes (open coding) by both researchers independently. After a few iterations and further discussion among the two researchers, themes were finalized along with notes on the context in which they came up in each interview via collaborative axial coding sessions. Notes from both researchers were then used to identify the frequency at which each theme came up. Themes were considered for the frequency count if at least one researcher identified the theme in their notes. Frequency analysis along with themes and their descriptions are shown in Table 4.3.

Table 4.3: Themes emerged from analyzing interview transcripts

	Theme	Frequency	Description
Robot Design:			
	Robot appearance/accessories	*7*	Participants discussed the appeal of robot appearance or suggested modifications to robot shell design and accessories

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[2] https://otter.ai/

	Robot noise and sound cues	*6*	Participants expressed preferences towards sounds generated by robot mechanisms
	Robot speed	*2*	Participants commented on the motion of the robot
Game Setup:			
	Teleop VS autonomous control	*3*	Participants engaged in a discussion regarding complete teleoperation vs partial teleoperation with autonomy features
	Number of children per robot	*8*	Participants were interested in exploring game settings where two children control a single robot VS where each child controls their own robot
	Difficulty of game	*7*	Participants were concerned with the difficulty of the game and its impact on interaction
	Impact of age	*4*	Participants discussed the impact of child age on collaboration scenarios and on the effectiveness of the robot in engaging children
	Competition VS collaboration	*4*	Participants showed interest in varying game mode between collaborative and competitive between children
Teleoperation and Feedback:			
	Teleoperation inputs	*9*	Participants suggested various input devices such as joysticks
	Using sound and light for feedback	*9*	Participants discussed the use of LEDs or sound as feedback from the robot
	Robot speech	*2*	Participants wanted the robot to speak to children
Potential Skills to Gain:			

	Communication and teamwork	*7*	Parents commented on the potential benefits of the robot for fostering teamwork and communication skills
	Perspective-taking	*3*	Parents believed the robot could help their children with regards to perspective-taking
	Gross and fine motor control practice	*7*	Parents believed the robot could be a potential therapeutic tool to overcome some motor challenges
Interaction with Digital Media:			in this section, children indicated what input devices they already use or have used to interact with digital media
	IPad/touch screen	*8*	
	Keyboard	*1*	
	Mouse	*2*	
	Voice	*1*	
	Gesture	*2*	
	Joystick/buttons	*5*	
	Eye tracking	*1*	

4.3 Findings

In this section, empirical results from the interviews are presented. Children shall be referred to with C, with an id number assigned to each family (e.g. C1). Similarly, parents will be referred to with P (e.g. P2).

4.3.1 First Impressions

Initially participants viewed the robot as a toy that their child would play catch with; they believed that the robot will be involved in a game where it could be controlled or teleoperated. Some participants had other expectations of the robot such as functioning as a "vacuum cleaner". C2 (male, 6 year old) thought it could help with everyday tasks:

"I want it to tidy up my toys". Other participants thought the robot would have other functions like drawing a picture, reading a story or answering basic questions. Multiple children expressed wanting to get a robot like the one they saw or felt happy upon seeing it (this was either stated or inferred from hearing their giggling). C3 (male, 7 year old) reported *"I feel happy when I see it (the robot)"*. P8 (daughter is female, 12) suggested giving themes to the game such as *"hungry hungry hippos"* as she thought the robot resembled a hippo. Other participants thought the robot resembled a turtle, a giraffe, a dog etc.

4.3.2 Robot Design

Opinions were mixed regarding the robot shell design; parents typically liked it but some wanted something more traditionally along the lines of cars, trucks or other toys that children are already familiar with. Children often referred to the robot as "cute", and the robot piqued the interest of younger children closer to 6 years rather than children closer to 12. The use of accessories to create customization was received well and parents and children excitedly suggested different options such as changing glasses, ears and color of the robot. After discussion with the researcher about custom 3D printed joysticks, P9 (parent of a 6 year old female) suggested matching the joystick design with the robot accessories to give it more personalization and make it easier on children to identify their own robot if there is more than one robot present in the playing field, *"It would be hard associating which one's hers. If they were at all similar, she would lose focus on whether it's this one that's hers or whether it's the other one or not... If one of the robots was in dinosaur mode, and the other was in sunglasses mode, maybe you have something that you can put on to the remote (joystick) for it that was similar. So for example, she could glance down and go, Oh, yeah, I have the robot with the red sunglasses"*.

Two parents noted that the robot's movements are noisy and thought it might scare children during in-person interaction. P9 stated, *"I was trying to look at her instant reaction. And I think she was taken aback a little bit because it's kind of loud... I only had my laptop so loud, and all that, like, it didn't scare her. But you could tell when it started to move. She sort of jolted back a little bit. I could tell it startled her...I think noise could make it seem scary to the kids."*.

On the other hand, four parents said the robot noise did not bother their child and would make for good feedback during interaction. P3 commented on the usefulness of the noise, *"My son, he can see but because his ears work better, he always tries to listen to what's being said, or what kind of noise something is making rather than like, watch it... he didn't mind that. He could hear the noise of the robot and he was smiling"*.

P5 noted the robot moved aggressively and quickly in the videos, *"I don't know how sensitive it is to the response of the controller but it seemed like it was kind of aggressive and pretty quick... my son who does not just have fine motor and upper extremities issues; he's also got lower extremity issues and he's not that mobile. So if he's on the ground, he's not gonna be able to like jump out of the way or move out of the way it's coming towards him or anything like that"*. Note, we designed the robot to allow fast movements that are suitable for ball games. It was never intended to be used with children who are moving or crawling on the floor, which would pose different safety constraints.

4.3.3 Game Setup

There were some concerns from parents about game difficulty and whether children could control the robot especially given its omni-directional movements due to the holonomic drivetrain. It is important to note that no explanation was given during interviews on how the robot is able to move omni-directionally as it was irrelevant to the study, and without proper background, parents and children would be confused with the explanation. Children did not raise such concerns and were rather interested in what the robot can do rather than how they interact with it.

Participants, especially children, had difficulties understanding the difference between the two proposed game modes: fully teleoperated and semi-autonomous, robot assisted. Additionally, when describing the semi-autonomous mode over the video call, it was sometimes misunderstood for the robot being fully autonomous and the child would simply "watch". P1 (daughter is female, 6 year old) understood semi-autonomy as being a much less involved mode *"I think children will be more engaged if they can control the robot ... so if the robot is moving by itself, it makes this more like a show or a movie"*. P5 was especially interested in semi-autonomy and even suggested adjusting the autonomy level automatically depending on the child's skill *"is that a setting that you set? Or is it does it automatically kind of feed into or sense based on the user input and then adapt accordingly?"*.

An important topic that was discussed in length in most interviews was whether to have one robot for each child or allow two children to control a single robot simultaneously. The researcher explained the 'two children to one robot' mode as allowing one child to take control of the robot motion and another child to take control of collecting balls and shooting them. The mode was generally received well but parents often mentioned the impact of age on the success of such mode. P4 (parent of a 6 year old female) was worried that the younger sibling for her daughter would have a conflict over controlling the robot with his sister *“It might create conflict and frustration for both of them ... even with two controllers (one for each child) I think that would be complicated”*. P6 (parent of an 11 year old male) expressed concern about how engaged two children at different ability levels would be, *“But I might imagine the other kids losing interest if it wasn’t like, very coordinated”*. P6 suggested a different play mode where one child (with disability) is controlling the robot and another child is playing fetch. *“I was imagining the child controlling robot, and then there being another child who was fetching the ball or giving the ball back to the robot. And in that case, I was imagining like a very young child who would fetch the ball and bring it back ... But when they get older, it’d be hard to keep a typically developing child attention. except in the case that you’re describing where cool, I get my own robot ... if both have these robots, they can play with each other”*. This topic sometimes led to discussions about collaborative vs. competitive game-play. Parents were usually unsure which game mode would better engage their children but they believed it would be beneficial to their social skills regardless of whether the game is competitive or collaborative. For example, P1 mentioned the importance of leveling the playing field for typically developing children and children with special needs, *“ I like the idea because right now the settings available for special children for for social play are very limited. Because of physical challenge of the special needs children, it’s hard for them to engage with typical children... if they can play together on a similar level field then they can engage mentally and socially”*.

4.3.4 Teleoperation and Interaction

An crucial topic that was discussed in all interviews was how children would teleoperate the robot. This was quite important as each child is unique with regards to their needs as no two conditions are the same. To gain insight into possible inputs, the researcher asked how the child interacts with electronics when attending online classes, playing video games, etc. One prominent input mentioned traditional joysticks, especially ones that require only one hand as some children were hemiplegic. One suggestion made by a few participants was using large buttons that are easy to press. P9 explained that it is hard on the child to hold an object, but pressing a button in a non-specific manner would be suitable, *“Maybe you could have a neutral and a forward and a back type of button that she could use with her whole hand as opposed to dexterity with your fingertips like holding a pen would be hard, but mashing a pedal wouldn’t be very hard”*. P2 emphasized that when using buttons, controls should be simple and should not force children to press multiple buttons at the same time. *“It should not be like a car game where you need to push continuously 2-3 buttons together because I saw that it might be complicated”*.

The most common input device used by children were touch screens especially due to the wide availability of free games and apps that are also accessible to children with special needs. Touch screens typically require less dexterity than a mouse and can be used with a finger rather than a full hand which is suitable for some children who do not have the fine motor control (i.e., slow and fluid motions) needed to use computer mice.

Voice inputs such as voice recognition were discussed but did not seem to be popular. P3 mentioned that her child already tried voice recognition but it was not practical, *"The other problem is that a lot of kids who have cerebral palsy, their speech is not clear. So for example, I may understand what he's saying. But like, for example, if you were to use Google speech to text, Google would not understand what he's saying"*. A family that had participated in accessibility research in their local children's hospital suggested using eye tracking if the robot was at the same level as the seat of the wheelchair. Other input modalities discussed included grasp and gestures, however, they were not favourable or practical to use as noted by parents.

As for feedback from the robot, children typically loved the lights emanating from the robot in the videos. The lights shown in the videos were green and static as opposed to the current version with dynamic lights. The researcher explained that the colors would change based on direction of motion and the patterns could be varied such as showing the light pulsating in a specific direction for further feedback. Though the light pattern shown to participants was neither complex nor dynamic, participants understood how it would be used during real interaction. They believed it would help children understand the robot's direction of motion and keep children interested by pulling their attention. P7 (parent of a 12 year old, female) suggested giving children the option to customize the LED color scheme to their favourite colors to further engage them *"most kids from what I know have favorite colors. If something can come in the color they want, they will be more engaged with the item"*. However, a few parents of epileptic children had concerns about brightness of LEDs as well as the rate of flashing that would be utilized *"flashing, super bright light does not work"* (P4).

Aside from the robot using lights for feedback, parents suggested using sounds such as celebration music when scoring a goal, or blowing a horn to draw attention, or even just playing music. P1 suggested using different sound cues to indicate the action of the robot *"So there can be some music to the robot. When when they score a different music plays and when they capture the ball maybe another music"*. Two participants suggested using speech to give the robot a "personality"; for example P4 suggested, *"Maybe it could talk a little bit and say for example 'Hey do you want to play ball?'"*. P3 suggested the robot should also talk from an educational point of view, *"It should describe things for example, the ball here is a green ball, the ball is small, it's a circle ... it would be good for learning"*.

4.3.5 Perceived Potential Benefits of the Robot

The robot was received positively by parents especially from a therapeutic perspective. In fact, some parents thought the robot was built to be used in therapy centers and suggested making it available for homes. Three main therapeutic themes emerged from analyzing interviews as shown in Table 4.3: communication and teamwork, perspective-taking skills and gross and fine motor practice.

Communication and teamwork was an especially prevalent theme because parents stated that their children, and children with special needs in general, do not get to play with their peers as often as they should. This was mainly due to the difficulty of creating activities that are engaging to both children with special needs and typically developing children. P1 talked about the level of inclusion in schools, *"Kids with special needs in schools are really hard to engage with the other kids. And so, like, something like that [the robot] will help the kids with special needs to engage with the other kids ... Because the school always talks about inclusion, but like, the level of inclusion is a thing that is really minimal"*. P4 expressed that children with special needs might be lagging behind on communication skills due to their isolation, *"She has limited words to express herself. So she can't really be at the same pace as kids her age ... If there was an adult to play with her, they kind of adjust their pace in their language"*. P7 was interested in a co-driving mode as she believed it would foster teamwork and turn-taking.

As the robot requires children to think of the robot's perspective especially when it turns to face them, some parents were excited about potential developmental benefits other than communication. They stated that, aside from perspective-taking, learning directions can be a benefit for children with severe challenges; *"So, okay, we are going to play a game with balls, but at the same time, we're going to work on above, left, right, straight..."* (P7).

Gross and fine motor control practice was also a prevalent theme. Many parents suggested game setups where there are underlying therapeutic benefits as to "challenge" children into using their limbs given they are motivated by the robot. P5 suggested bimanual tasks for children with cerebral palsy, *"I think anything that could encourage bimanual, without being too frustrating would be good. So I guess you can adapt controllers to like putting them on a stand or something like that so you don't have to hold it with the other hand"*. P6 mentioned that children with hemiplegia would benefit from teleoperating the robot if it is set up correctly, *"He would be able to sort of position his left hand over something that he would grasp, and then make the right hand grasping motion which would cause the left hand to grasp. And it could be useful practice for other functional things"*.

4.4 Discussion

Many participants noted being unsure about their first impressions as it was difficult for both children and parents to visualize the robot through pictures and video only. This was also true for the proposed playing field and space as it did not make much sense prior to receiving more detailed explanations by the researcher during the online calls. While it did create some misconceptions, this can be viewed as a positive point, as it allowed participants to be creative and make some suggestions that researchers did not anticipate. Priming participants with our questions was a big concern as we could not conduct the in-person co-design studies we had planned before COVID-19 restrictions. However, these small misconceptions caused by viewing pictures and videos before the call, allowed for a more diverse discussion whilst still being able to get feedback after the researcher clarified said misconceptions.

From discussions with participants, it seems the shell design was a success as it was able to elicit positive reactions from children by being perceived as "cute". Similarly, accessories were a welcome addition especially the glasses. Children attributed the shell design to many different animals as mentioned above. This variation could be due to the difficulty of determining scale in pictures and videos shown to the participants (especially for children). Parents often suggested the robot shell design should represent more familiar toys such as cars or trucks. This could improve engagement in older children as we noticed less engagement from participants closer to the age of 12.

Mechanical sounds generated by the robot during operation seemed to be an issue for some participants but not for all. While it could due to high volume settings on participants' computers, loud noises from the robot are a valid concern and is being improved incrementally. In real human-robot experiments, the motor noise of robots can often serve as a cue and help participants understand the robot's movements, but of course the noise should not distract or impair the interaction experience for participants. Carrying out such studies remotely is a significant challenge.

Individual interviews with families were quite useful as they got the chance to participate in in-depth discussions as opposed to the potentially limited speaking time of a focus group. Additionally, the online format of the interviews allowed us to interview participants from all across North America ensuring diversity of responses. That being said, this approach is not as scalable as online group settings such as the one proposed recently by Tian et al. where they used group video calls, interactive interfaces and group discussions to facilitate user-centered design over multiple sessions [93]. Originally, we had hoped for a much larger sample size. The limited number of families who participated despite an intensive recruiting process that lasted over several months could be attributed to the timing of the study. Recruitment started by the end of August and went on until the end of September 2020, which is the period when schools resumed operation. Families with children with special needs were especially affected by the pandemic and had an additional challenge of adapting their children's computing setup to the online learning environment. During the pandemic, parents were particularly struggling with coordinating work, school work, and care obligations. In fact, one of the interviews was cut short and resumed at a later time because the parent had other duties. During the pandemic parents might have been reluctant to take on additional activities and demands on their time, which could have led them to ignoring emails about online studies involving their children. Additionally, some accessibility organizations that were contacted but were not very responsive, could have been overwhelmed as they needed to assist their clients given the unusual circumstances and disruptions to their lifestyles.

With reference to RQ2, using our interview methodology, children did not provide as many suggestions or participated in the discussion as much as their parents. Given that interviews were conducted with parents and children together, it might have been difficult for children to voice their own opinions when it comes to decisions about how technology should be used. The difficulty stems from the power structure of the "all-knowing" adult as Druin suggests [94]. However, having parents observe and interpret their children's reactions and relaying them to the researcher was quite useful especially because of the communication barriers with some children with special needs. Moreover, a possible reason for children's limited participation could be that the robot's design and functionality was too unfamiliar. Yip et al. ran intergenerational co-design sessions at the University of Washington and found that some children have trouble extending their imaginations and stuck to designing what they already know; for example, a 9 year old boy kept drawing cubes because it was something he was already comfortable making [95]. Vaajakallio et al. suggested that adult facilitators may be needed to guide the conversation and encourage children input by connecting design ideas and concepts to their everyday lives [96]. Thus, giving parents specific instructions on how to facilitate the interview could have been helpful in encouraging children to participate more pro-actively and voice their input, however, it would have also added workload to the parents.

Overall, the interviews provided a lot of useful feedback and were an important stepping stone towards the completion of the project. Currently, we are collecting survey responses (survey shown in appendix) from therapists in a separate study, which will be complementary to the interviews discussed in this chapter.

(a) (b)

Figure 4.2: Interface of robot based on feedback: (a) Microsoft Adaptive Controller is shown on the left and a prototype for our custom 3D printed joystick is shown on the right. (b) Custom joystick redesigned to be slightly more ergonomic along with added imprints that match the customization of robot ex: glasses, ears etc

4.5 Lessons Learned

Diversify Participants: From the start, we attempted to limit the scope of the robot's design in order to have an impactful robot that could target a certain population (children between 6-12 with upper limb challenges). However, this focus was not sufficient as there are many conditions that could cause such challenges. Moreover, even within the same condition such as hemiplegia, there are many factors causing the condition, and symptoms and needs that are not necessarily similar for different individuals. Speaking with different families helped advance the design further and increase the accessibility of the robot.

Controller Design: As mentioned in the design process section, the interface was not designed prior to the interviews as it has a significant impact on the usability of the robot. It seems unanimous that large motions and simple push/touch controls are the easiest to use and will accommodate each child. This calls for controllers with large buttons and joysticks with adjustable sensitivity. In order to maximize therapeutic benefit, both hands should be used if the child is able to use both, even if minimally. Given this feedback, it is recommended to use large buttons that do not need a lot of force to press. Additionally, we learnt that the controller needs to be easy to see for children with vision challenges. Thus, the Microsoft Adaptive Controller [3] seems to be a suitable choice as it has two large buttons

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[3] https://www.xbox.com/en-CA/accessories/controllers/xbox-adaptive-controller

and could be mounted on wheelchairs easily. Moreover, it allows for custom inputs which we plan to design in the near future. Based on feedback, a custom joystick has already been designed incorporating factors such as ease of manipulation and being larger than the average joystick which is difficult to use according to discussions with participants. The custom joystick includes engravings to indicate which accessories the robot is using which would help children identify their robot if more than one robot is used.

Importance of Adaptive Behaviour: An important point that was brought up during some interviews was that some children feel isolated due to their condition and avoid interacting because they cannot keep up with their peers. Children with special needs seem to require different levels of accommodation based on their condition. This gives emphasis to semi-autonomy as a basic feature of the robot. Semi-autonomy needs to be adjusted dynamically based on the child's performance which calls for a metric to measure a child's performance when interacting with the robot. This is not necessarily as trivial as using the child's performance/score in the game. The robot is already able to track game objects, collect them and score a goal, however, it will be challenging to adjust autonomy to give children enough freedom and independence to enjoy the game whilst keeping an accessible play activity.

Importance of Sound: The project initially had multi-color lights as the key feedback method such as indicating the direction of the robot by changing colors or showing "happy" states such as a rainbow when a goal is scored. After the interviews, we decided to add a speaker to the robot and make it produce sounds to further engage participants as many of them expected some form of audio communication. We initially avoided speech to prevent raising children's expectations of the robot's intelligence and to prevent the robot from becoming the center of the activity rather than child-child interaction. However, basesd on the feedback we received during the interviews, we are adding simple sound cues such as a celebratory tune when scoring a goal.

Therapeutic Aspects: The initial concept of the project was to facilitate child-child interaction through child-assisted play. After talking with therapists and interviewing families, it seems beneficial to account for a therapeutic aspect for children with special needs. For example, using the robot as a motivator to perform arm exercises or configuring the joysticks to encourage bimanual control. There are already many examples of using video games for therapy and rehabilitation purposes in the literature, and there is potential to add therapy as a side goal for this particular project.

Chapter 5

Target User Simulation and Adaptive Assistance Model

This is a two part chapter: (1) I discuss simulating difficulties that children with upper limb mobility challenges face, and (2) I present preliminary work on adaptive user assistance. All work presented in this section needs validation through in-person experiments with children when such experiments become possible after COVID restrictions are lifted.

Work in this section was motivated by two research questions:

- **RQ1.1:** Can we simulate robot teleoperation difficulties that face individuals with special needs, specifically upper limb mobility challenges such as CP?
- **RQ1.2:** Can we use expert feedback during teleoperation to build an adaptive assistive system that does not interfere with gameplay?

5.1 Simulating Upper Limb Mobility Challenges

Due to COVID-19, in-person research was paused for long durations of 2020-2021. This interfered with the original plan of collecting data from children interacting with the robot through teleoperation. Without such data, it is quite difficult to build an adaptive system that accounts for the challenges they face without interfering with the game; too much assistance, interferes with the challenge of the game and could make it uninteresting.

One step to address the above issue was conducting interviews with the target population to understand their challenges and needs as mentioned in the previous chapter.

Additionally, I turned to available literature on simulating hand mobility challenges in HCI and HRI as discussed in the literature review section. Although there is no simulation framework for robot teleoperation for children with special needs, there were a few attempts at creating simple models of hand movements for CP. I found that users with CP may experience:

- Force deviations in lateral direction with respect to the intended direction of application.
- Decreased force applied by their hands compared to healthy users.
- Multiple deviated sub-movements in random directions near the beginning and end phases of a given trajectory.
- Possible delays due to perceptual challenges besides physical challenges.

While it is possible to simulate these challenges by applying them to a simulated trajectory, it would not be realistic to do so because humans may not have an “optimal” trajectory in mind when playing a game. Georgiou and Demiris created an adaptive model that modulated track difficulty for a car racing video game based on the user’s experience, level of exploration and engagement in the game [97]. Due to time limitations, instead of creating a simulated trajectory based on different factors such as experience, exploration and engagement, We decided to “distort” input from healthy users. That way, trajectory is generated by various human users with different levels of experience with robotics. Distorted input is based on what I found in literature regarding users with CP and based on our interviews with children with upper limb mobility challenges. To the best of our knowledge, such a distortion module for teleoperating robots has never been done before. The simulation is important in early stages of developing accessible technologies, and can be generalized to many applications such as wheelchair teleoperation or other kinds of robotic teleoperation. The goal of the distortion module is not to subject healthy users to the challenges that individuals with special needs face. Some “simulation” activities are usually done to allow members of the public to experience accessibility challenges by asking able bodied individuals to spend some time in a wheelchair. While these simulation activities have reported that able bodied individuals new insights into accessibility barriers [98], they would not work for gameplay. Restricting input to a game and have the robot perform actions that are not expected interfere with gameplay and could result in able bodied users losing interest in the game.

5.1.1 Distorting healthy users' input

To deliver distorted velocity commands to the robot, we first obtain healthy user commands as linear and angular velocities and perform the distortion as a fraction of the input value depending on the experimental condition. The distortions may be applied individually or simultaneously. I chose to apply the following distortions:

- **Goal deviation:** takes a fraction of the intended direction and applies it in the normal direction. For example, the algorithm takes a fraction of x velocity and applies it to the y direction to create a deviation.
- **Noise:** applies noise to the yaw velocity of the robot (rotation). The noise is generated by sampling a value from a gaussian distribution with mean 0 and standard deviation of 1, and multiplying the value by the "noise level".
- **Force modifier:** simulates a reduced pushing force on the joystick by multiplying the input velocity by a force modifier that is between 0-1. This essentially slows the robot down because the teleoperation velocity is directly proportional to how far the joystick is pushed.
- **Input delay:** this delays commands sent from the user to robot actuators by a set amount of samples. Please note the samples are asynchronous and are only sent to the robot when the user changes the velocity values by moving the joystick.

Overall, the velocity of the robot is distorted as follows:

$$vel\_x[n-d] = \begin{cases} vel\_x[n-d] * \text{force modifier} & \text{if} |vel\_x[n-d]| >= |vel\_y[n-d]| \\ vel\_x[n-d] + vel\_y[n-d] * gd & Otherwise \end{cases} \tag{5.1}$$

$$vel\_y[n-d] = \begin{cases} vel\_y[n-d] * \text{force modifier} & \text{if} |vel\_y[n-d]| >= |vel\_x[n-d]| \\ vel\_y[n-d] + vel\_x[n-d] * gd & Otherwise \end{cases} \tag{5.2}$$

$$vel\_z[n-d] = vel\_z[n-d] * \text{force modifier} + \text{rand} * \text{noise} \tag{5.3}$$

Where vel_x and vel_y are linear velocities in the x and y directions in the robot's coordinate frame, and vel_z is the yaw (rotational) velocity in the robot's coordinate

Table 5.1: Experimental conditions for testing the distortion of healthy user input

Condition	**Parameter value**
#1 Undistorted	Goal deviation: 0 Noise: 0 Force modifier: 1 Delay: 0
#2 Slight distortion, full force	Goal deviation: 0.4 Noise: 0.2 Force modifier: 1 Delay: 0
#3 Slight distortion, half force	Goal deviation: 0.4 Noise: 0.2 Force modifier: 0.5 Delay: 0
#4 Heavy distortion, half force	Goal deviation: 0.7 Noise: 0.5 Force modifier: 0.5 Delay: 0
#5 Heavy distortion, half force and with delay	Goal deviation: 0.7 Noise: 0.5 Force modifier: 0.5 Delay: 5 (samples)

frame. n is the current sample and d is the delay in samples. gd is the goal deviation with range 0-1. The *rand* term refers to a random sample drawn from a normal (Gaussian) distribution, and *noise* refers to the noise level assigned to the yaw velocity of the robot.

It is important to note that this distortion system has not been validated with data from children with special needs, and was rather tested internally as a proof of concept.

5.1.2 Testing the Distortion Algorithm

The proposed system was tested with 9 healthy participants, however, only data for 8 users is presented in this chapter because data did not record properly for one of them. We

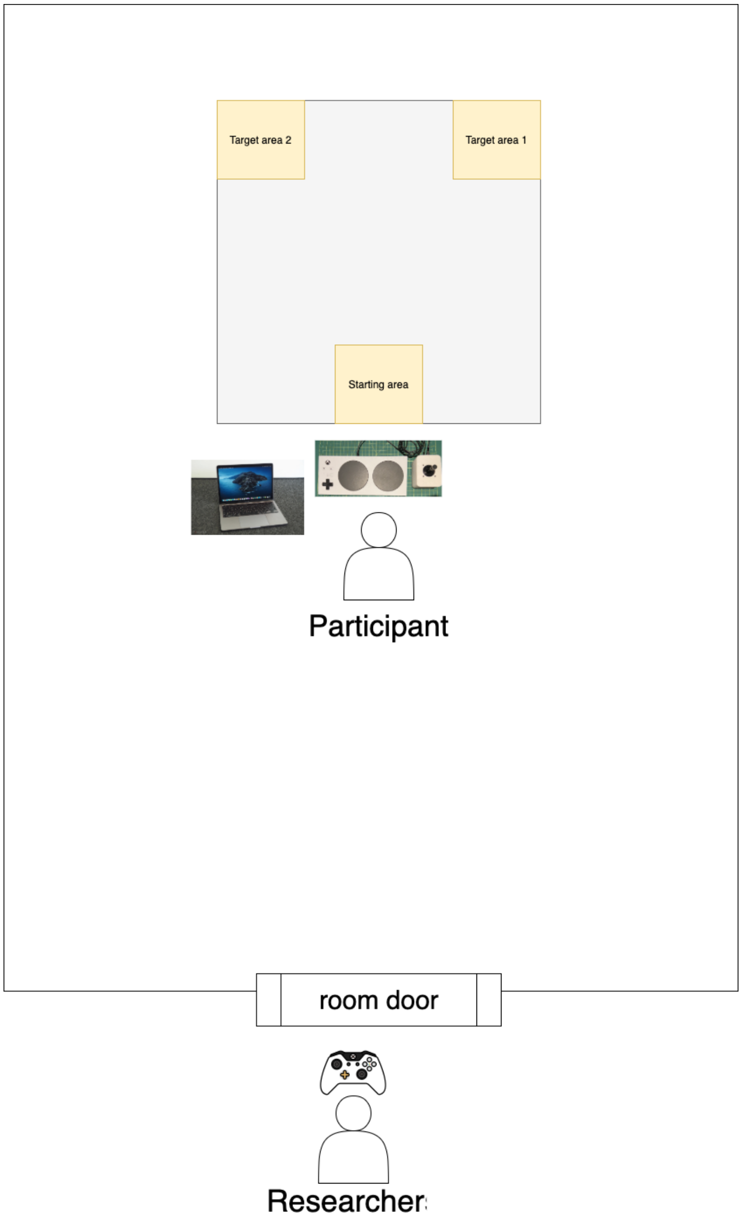

Figure 5.1: Experimental playing field used to test the distortion algorithm. The robot resets all measurements and starts in the starting area, and users are instructed to teleoperate it to one of the two target areas shown. The researcher stands outside the room due to COVID safety considerations.

Table 5.2: Prior experiences of participants. * signifies a prior experience is present.

Participant	Experience with robot teleoperation	Experience with joysticks and video games
1	*	*
2	*	
3		*
4		*
5	*	*
6	*	*
7	*	*
8	*	*

were only allowed to recruit participants from among our own lab members who already work in the lab regularly (the Social and Intelligent Robotics Research Lab (SIRRL)). This was due to COVID restrictions which prevented us from recruiting anyone who is not already approved to work in the labs. Participants were graduate students and post-docs who were recruited through the lab's mailing list. They were asked to complete a consent form digitally along with two questions: (1) a question about their prior experience in teleoperating robots, and (2) a question about their prior experience using joysticks for video games. University-approved COVID safety protocols were followed throughout the study, and no contact took place between the researcher and the participants as shown in Fig. 5.1. Interaction was kept short to avoid risks of COVID infection and equipment (joystick shown in Fig. 4.2) was thoroughly sanitized in between tests. The tests included a familiarization phase where the participant teleoperates the robot without distortion and without any given objectives. Afterwards, participants were instructed to move to one of two pre-defined areas on the field. Each distortion condition was tested with the robot teleoperated to target area 1, then the robot would be reset to the starting area, and teleoperated to target area 2. The steps were repeated for each condition shown in Table 5.1.

Participants were instructed to use the custom joystick designed after the interview study as discussed in the previous chapter. This also served to test and confirm that the design is adequate for teleoperation, though I cannot draw any conclusions from this setup. The distortions made teleoperating the robot more difficult and necessitated some assistance from the supervisor who was co-teleoperating the robot. The supervisor only stepped in to assist when necessary, and used a typical XBOX One joystick [1] to co-teleoperate the

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[1] https://www.xbox.com/en-CA/accessories/controllers/xbox-white-wireless-controller

robot. Input commands from the supervisor overwrote the participant commands.

5.1.3 Data collection

The distortions were configured as ROS parameters which allowed for ease of setting up/monitoring experiments. Data was collected using the *rosbag*[2] package which allows to record any ROS topics available to the system, and stores messages published to said topics in a compressed file format. All data was timestamped and collected asynchronously to permit various refresh rates.

Data was collected from the robot's sensors such as Odometry, as well as the participant's distorted inputs and the supervisor's inputs. The original plan was to use and record the on-robot camera, however, when running all 9 ROS nodes along with computer vision and data recording, the robot's computer would restart due to overheating. To mitigate this problem I modified the original plan (which was to allow users to go after balls and pick them up), to what is shown in Fig. 5.1. With the balls removed, a camera was not needed to find them, rather, the robot can start at a preset starting point and go to a predefined target zone. Please note that without data recording, vision runs without issues on the robot.

Overall, I collected 10 runs for each participant; they were instructed to go to goal 1, reset then go to goal 2 for each condition. With 40 runs in total, I was able to use the data formulate an assistive model as discussed in the next section.

Although I did not collect the participant reactions systematically as part of the study, it is worth noting that most participants noted increasing difficulty as the study progressed, and felt like they had little control in the heavy distortion conditions.

5.2 Building an Adaptive Assistive Model

As mentioned earlier, it is imperative that the robot provides dynamic assistance based on the user's teleoperation ability. An assistance as needed (AAN) strategy is quite popular in the rehabilitation robotics literature. Typically, the assistive algorithm provides force feedback to the user who interfaces with a force feedback capable joystick. MyJay is intended to be open-source, and one of the goals is to keep it low-cost. To reduce cost, I chose to go with a custom designed joystick that does not provide force feedback, and

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[2] `http://wiki.ros.org/rosbag`

instead, it snaps back into position using passive elastics when released. Following our strategy is a bit tricky because it has not been tested in the literature. With force feedback, the user gets a sense of the assistance, however, in our case, assistance may not even be apparent.

Assisting without force feedback makes sense in our case because our goal is not necessarily motor rehabilitation, rather, creating joyful play sessions and building connections between children using the robot as a mediator for play. This mode of assistance constitutes "nudging" the robot in the direction a child is trying to follow. A similar system has recently been patented by Sony for video games: "The patent also covers the possibility of a game being able to notify a player if they are struggling to complete a task that the AI can assist them with" [3].

AAN can be accomplished by many techniques such as rule-based expert systems [58], controllers formulated through control theory [55, 54], or using probabilistic methods such as learning from demonstration (LfD) [60]. I believe LfD has advantages such as encoding non-intuitive rules, and allowing experts to provide personalized feedback non-verbally through direct teleoperation of the robot. Assistance should depend on context, for example, a child might pause playing for a few seconds because they got distracted, or they may be exploring different strategies to play the game. While rule-based systems can incorporate many cases (even edge cases), it would take a lot of programming to incorporate new rules to the system. Alternatively, by collecting data of new users during gameplay, and allowing experts to give real-time feedback, rules accommodating even new players can be incorporated through data-based machine learning methods. A data based method would allow to encode personalized rules for specific children and specific supervisors who might provide different feedback depending on their relationship with the child. One promising method is Gaussian Process (GP) regression [99], which has been used to assist in driving power wheelchairs safely in one-shot (single demonstration) learning sessions [60]. Although our case (gameplay) is a little different, I believe with enough data, this method can provide effective AAN. Aside from GP, I explore popular methods for regression, namely, neural networks (NN), support vector regression, and regression trees.

Models were evaluated using the coefficient of determination regression score function. The coefficient of determination is defined as the proportion of the variance in the target data which has been explained by the independent variables in dataset [100]. Mathematically, it is defined as follows:

$$R^2(y, \hat{y}) = 1 - \frac{\sum_{i=1}^{n} (y_i - \hat{y}_i)^2}{\sum_{i=1}^{n} (y_i - \bar{y})^2} \tag{5.4}$$

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[3] https://www.pcgamer.com/sony-patents-an-ai-bot-that-will-play-your-games-for-you/

Where R^2 is the coefficient of determination, $\hat{y}$ is the predicted value of the i-th sample and y_i is the corresponding true value. The best possible value of the coefficient is 1.0, however, it could be arbitrarily negative depending on how far predictions are from target values (value can be smaller than -1).

5.2.1 Gaussian Process Regression

GP regression is a supervised learning methods which could be used to solve regression problems because it offers continuous output [99]. Additionally, it accepts continuous input meaning we do not have to discretize the robot states in order to get a prediction [99]. This fact is true for the other 3 regression methods used in this chapter. Predictions (or regressions) generated by GP have a confidence interval which allows the designer to evaluate the model and retrain if necessary. Different kernel functions can be used to construct GPs allowing for flexibility in modelling for different datasets [99]. Additionally, it has been shown that there is an exact equivalence between infinitely wide deep neural networks and GP [101]. However, GPs do not come without disadvantages: (1) they cannot deal with sparse datasets, meaning they need a whole sample to train or make a prediction [99], and (2) they are incredibly inefficient for a large datasets since they require the Cholesky decomposition which takes $O(N^2)$ space and $O(N^3)$ time complexity [99].

A GP is composed of a collection of random variables $X_1, .., X_n$ belonging to a set χ, where χ is a finite subset and the marginal density $p(X_1 = x_1, .., X_n = x_n$ is a multivariate Gaussian [99]. Just like any Gaussian distribution, a GP, can be fully defined by its mean and covariance matrices [99]. The covariance function is quite important in a GP, and luckily, it can take any form as long as it is a symmetric positive-definite matrix [99]. The covariance function is also typically known as the kernel, and there are many popular kernels such as constant kernels, the radial basis function (RBF), the Matérn kernel, and even neural networks! [99]. In short, a GP estimates an unknown function f given training data y (noisy observations) at a finite number of points x:

$$\begin{gathered}\left[\begin{array}{c} f\left(x_1\right) \\ \vdots \\ f\left(x_N\right) \end{array}\right] \sim \text{MultivariateNormal}\left(\text{loc}=\left[\begin{array}{c} \mu\left(x_1\right) \\ \vdots \\ \mu\left(x_N\right) \end{array}\right], \text{ scale }=\left[\begin{array}{ccc} k\left(x_1, x_1\right) & \cdots & k\left(x_1, x_N\right) \\ \vdots & \ddots & \vdots \\ k\left(x_N, x_1\right) & \cdots & k\left(x_N, x_N\right) \end{array}\right]^{1/2}\right) \\ y_i \sim \text{ Normal }\left(\text{loc}=f\left(x_i\right), \text{ scale }=\sigma\right), i=1..N \end{gathered} \tag{5.5}$$

Where μ is the mean of feature x and and k is the covariance function.

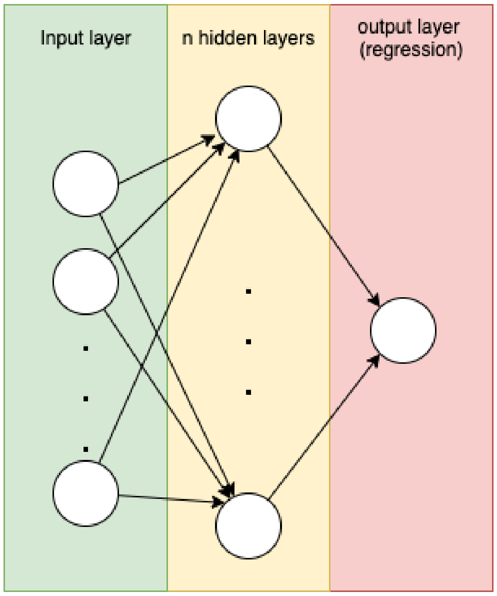

Figure 5.2: General Architecture of a multi layer perceptron. Circles refer to individual neurons.

I chose the RBF function to its simplicity (has only two parameters), and it being considered a "universal kernel"; that is, it can approximate a continuous function uniformly on any subset of the input space [102]. The function can be defined as follows:

$$k_{\mathrm{RBF}}\left(x, x'\right) = \sigma^2 \exp\left(-\frac{\left(x - x'\right)^2}{2\ell^2}\right) \tag{5.6}$$

Where σ is the variance of the function and ℓ is the "length scale" factor, which prevents extrapolation more than ℓ units away from the data [103]. Finally, I chose marginal log likelihood as the model loss and the adam optimizer for training the model.

5.2.2 Neural Networks

Given the simple nature of the dataset (only 10 features), a simple NN should suffice for the task. A multi layer perceptron (MLP) architecture [104] was used to build a regression function for our dataset. MLP is known as a fully connected, feedforward network, composed of "neurons" at each stage as shown in Fig. 5.2. Each neuron has the following form:

$$a = \phi\left(\sum_j w_j x_j + b\right) \tag{5.7}$$

Where a is the neuron activation, ϕ is the activation function of the neuron, x is the input, w refers to the weights and b is the bias of the neuron.

NN are quite well discussed in the literature, and going into the details of how they're trained is outside the scope of this thesis. For the results shown in this chapter, I used a network with 10 input neurons (10 input features), 2 hidden layers with a ReLu activation function [105], and 1 neuron in the output with linear activation. Aside from architecture, I used the mean square error as an objective function and the adam optimizer for training.

5.2.3 Support Vector Regression

The support vector (SV) algorithm is widely used for both classification and regression purposes [106]. SV regression (SVR) is a supervised method which finds a function f(x) that has the most deviation from target values (y) without surpassing an error threshold ε [106]:

$$f(x) = \langle w, x\rangle + b \text{ with } w \in \mathcal{X}, b \in \mathbb{R} \tag{5.8}$$

Where x is the input, w are the weights, b is the bias and $\langle ., .\rangle$ is the dot product in $\mathcal{X}$. To solve for f(x) in 5.8, the following optimization problem is formulated:

$$\begin{aligned} &\text{minimize} \quad \frac{1}{2}\|w\|^2 \\ &\text{subject to} \begin{cases} y_i - \langle w, x_i\rangle - b \leq \varepsilon \\ \langle w, x_i\rangle + b - y_i \leq \varepsilon \end{cases} \end{aligned} \tag{5.9}$$

There are a number of details/modifications to the problem formulated in 5.9 in order to make it feasible (as we're operating with the assumption that f(x) exists). Discussing the details is outside the scope of this thesis, and they can be found here in [106].

One advantage of SVR is the ability to perform the "kernel trick", in which inputs are transformed to another space using a kernel function $\phi(x)$. This allows modeling non-linearity in the input data. An RBF kernel was chosen for the model used in this chapter, for reasons similar to the reason I used the RBF kernel in GP. Aside from the kernel, I used a C value of 1.0 and set the max iterations to 10000 for the optimizer.

5.2.4 Regression Trees

Regression trees are based on decision tree classifiers which are another supervised learning method [107]. Trees consist of branches which represent conjugations of different input variables, and leaves which represent target class labels [107]. Branches are formed by splitting nodes according to a certain input feature. Splitting is based on a criteria to define the best feature at a given node. This is determined based on metrics such as Gini impurity or information gain [107], and searching for the best feature is usually a greedy search [108]. Decision trees have discrete class labels while regression trees have class labels than can take continuous values. For the model in this chapter, I used the mean square error to determine the quality of each split.

5.2.5 Pipeline Setup

I attempted to use all useful data from the robot's internal states such as position, velocity and orientation. The dataset consisted of 10 features: user angular velocity commands, user linear velocity commands (both x and y), robot position on the field (both x and y), robot linear velocities (both x and y), robot angular velocity, robot linear acceleration (both x and y), and the robot's orientation. The target variables are the supervisor's velocity commands (x, y, and angular (yaw)). Originally, instead of the robot's position on the field, I wanted to use the ball's position relative to the robot, but due to limitations in the robot's computing unit while recording data, I decided to forgo vision for this "proof of concept" experiment. Additionally, I wanted to incorporate gameplay time as another feature, but with the current setup, it does not represent a realistic gameplay session, and thus, time in this dataset would not transfer well to actual gameplay scenarios.

After recording data in *rosbag* files, it was extracted into pandas dataframes where it was made not sparse; because *rosbag* records data as it comes, some samples may have values for only some features, while the others would be empty. To remove sparsity, I filled sparse rows of features with the latest value of the feature. After, data was saved into CSV files for later use.

5.2.6 Training and Results

Training was performed using various libraries because different implementations offered optimized run-times and use of GPU where possible. For GP, the GPyTorch framework[4],

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[4] https://docs.gpytorch.ai/en/stable/index.html

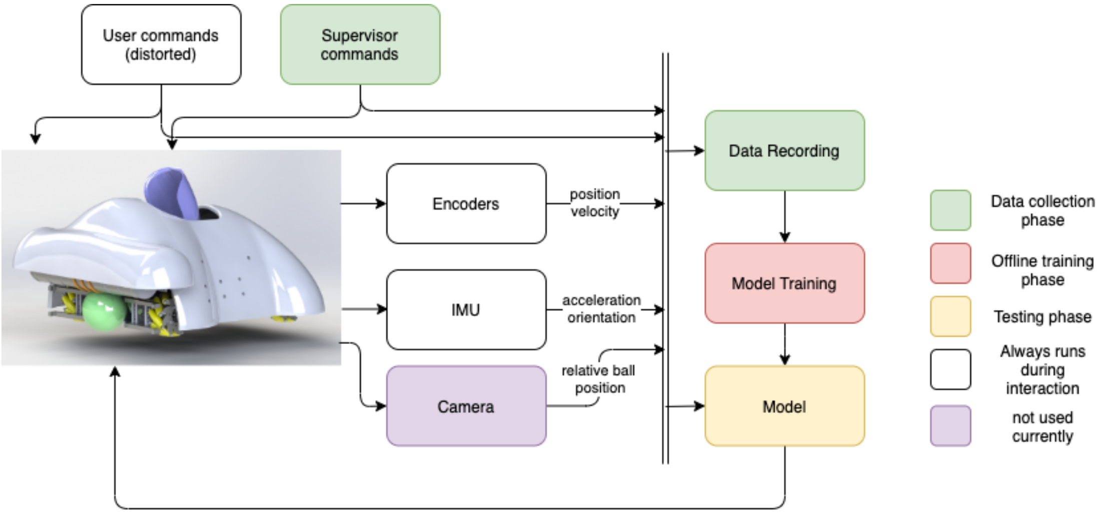

Figure 5.3: Data pipeline for the learning from demonstration setup.

which is based on the popular PyTorch machine learning framework [109]. The framework was chosen because it supports GPU acceleration for GPs which is desired especially with the large time complexity of the algorithm. The MLP was implemented using the keras framework with Tensorflow backend [5] due to its simplicity and GPU support. SVR and regression trees were implemented in the sklearn framework [6]. Please note that regression trees in sklearn are implemented as CART (Classification and Regression Trees). Training was performed in a Google Colab environment [7].

GP has a serious memory disadvantage and only worked effectively for smaller subsets of the dataset. Even when training was split into batches, it was not effective in learning an AAN function. To overcome this challenge, data was split per user and separate models were trained for each user. Additionally, separate models were trained for each output (x velocity assistance, y velocity assistance and yaw velocity assistance) because of the one class limitation imposed by the support vector regressor in sklearn. The dataset was split 80/20 for training/testing.

Performance of each model on different users is shown in Table 5.3, and cases where the model learned to assist are highlighted in bold. I attempted changing hyperparameters for each model but that did not result in significant improvements or changes in each

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[5] https://keras.io/

[6] https://scikit-learn.org/

[7] https://colab.research.google.com/

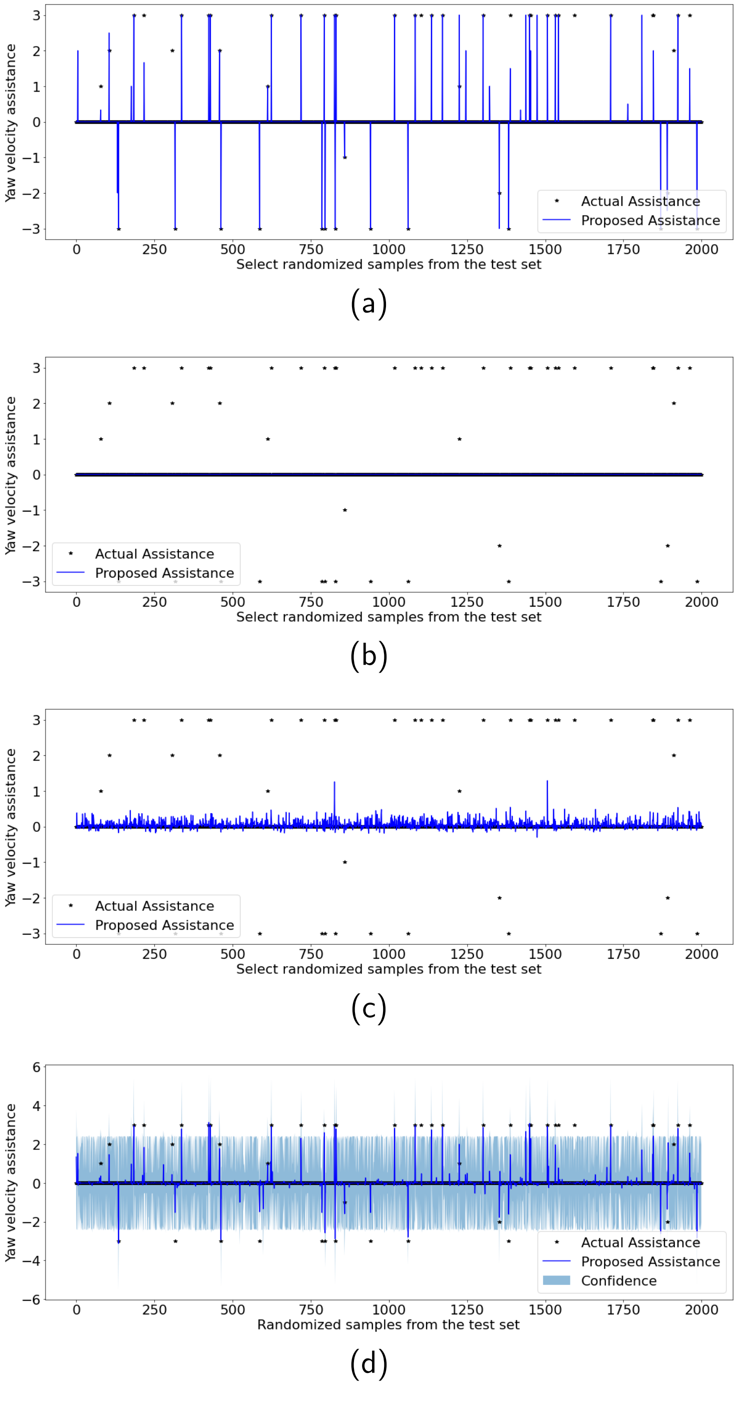

Figure 5.4: Proposed yaw velocity assistance from various models on randomized samples from the test dataset (user 1): (a) regression tree, (b) SVR, (c) MLP, and (d) GPR

Table 5.3: Coefficient of determination score resulting from different learning strategies for the AAN algorithm (using 10 time cross validation). Note: P stands for participant.

Method	**Dim.**	P 1	P 2	P 3	P 4	P 5	P 6	P 7	P 8	combined
Tree	x	**0.849**	**0.529**	**0.525**	**0.822**	**0.583**	**0.817**	**0.862**	**0.799**	**0.782**
	y	**0.779**	**0.794**	**0.835**	**0.781**	**0.818**	**0.782**	**0.835**	**0.805**	**0.749**
	yaw	**0.674**	**0.631**	**0.780**	**0.609**	**0.610**	**0.735**	**0.643**	**0.733**	**0.684**
SVR	x	-0.027	-0.006	-0.003	-0.030	-0.007	-0.025	-0.046	-0.032	-0.023
	y	-0.060	-0.023	-0.057	-0.048	-0.016	-0.001	-0.033	-0.013	-0.027
	yaw	-0.009	-0.024	-0.001	-0.015	-0.006	-0.056	-0.003	-0.014	-0.012
MLP	x	0.136	0.112	0.049	0.235	0.035	0.167	0.171	0.160	0.103
	y	0.128	0.191	0.186	0.228	0.142	0.147	0.105	0.109	0.095
	yaw	0.067	0.168	0.125	0.143	0.163	0.154	0.110	0.200	0.096
GPR	x	**0.440**	0.022	0.015	0.300	0.003	0.170	0.280	0.190	N/A
	y	**0.635**	0.222	**0.493**	**0.686**	0.005	0.175	0.024	0.115	N/A
	yaw	**0.681**	**0.728**	0.365	**0.621**	**0.442**	**0.410**	0.357	0.348	N/A

model. Regression trees performed quite well in both individual and combined cases. SVR performed the worst, with negative coefficients of determination across the board. MLP showed some improvement when trained, with some coefficient of determination values getting close to 0.2 for individual cases. GP showed promising results for individual cases, however, it was not possible to train it on the combined user dataset due to memory limitations.

5.2.7 Discussion

From table 5.3, we can see the AAN algorithm provides useful assistance that is close to the supervisor's assistance. Effectiveness or the "goodness of the fit" is shown using the coefficient of determination metric. While the metric allows us to compare how different models perform relative to each other, we cannot make any conclusions about whether the AAN algorithm performs better than a "no assistance" condition. This needs a separate future study where different models are used, and a metric for the improvement of the interaction is used. Improvement of an interaction is not trivial, and cannot be measured with performance such as time to get to a target.

There is an apparent disparity in terms of the coefficient of determination score between different users for the same type of model. The reason could be attributed to the lack of comprehensive examples for each user, which is a product of the simple experimental setup. A longer experiment and more conditions may be needed bring about a more even performance for different models of the same type across different users. That being said, different models for each user may not be needed. Table 5.3 shows that when combining data from all users, it was still possible to create a model that performs comparatively well with respect to models created for individual users.

Instead of discussing whether each model can provide assistance, it is more practical to ague for the feasibility of each model in a future study where the AAN algorithm can be tested for effectiveness. Regression trees show strong performance relative to the other methods presented in table 5.3, and do not face the same computation/memory limits present in GPR which seems to require multiple GPUs on large datasets, and GpyTorch recommends that multiple GPUs are used for datasets larger than 10,000 samples [8]. Thus for future studies to validate the AAN algorithm, regression trees should be used, and their performance can be improved by using ensemble methods such as random forests.

Future iterations of the AAN algorithm should include time as an input to the model. Time is an important factor in gameplay and can be indicative of whether the player is facing a challenge or not. It was not included in the model presented here because of the simplicity of the task, but it could be a valuable input. The joystick used in this study needs to be validated as an input method in an experiment with children with accessibility needs. The algorithm seemed to correct the distorted teleoperation signals in accordance with the supervisor corrections, however, when collecting data, more distortion conditions should be explored (given the distortion algorithm has been validated in the first place). Finally, it is quite important to use vision and actual gameplay scenarios, rather than the procedures presented in this chapter. The procedures were limited due to the compute module overheating problem when running vision. This can be fixed by either improving code efficiency or getting a better compute module.

5.3 Summary

In this chapter, a novel method was presented for simulating difficulties that individuals with upper limb mobility challenges (such as CP) face. The method has potential for quick testing of designs whilst accounting for accessibility needs. There has been a simulation method proposed for making accessible designs of computer programs in human-computer interaction [68]. However, substantial work is yet to be done in the field of human-robot

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[8] https://docs.gpytorch.ai/en/stable/examples/02_Scalable_Exact_GPs/index.html

interaction to simulate such challenges. Rather than designing a cognitive system that generates command velocities for specific tasks on its own, the approach presented in this chapter taps directly into command velocities and does not require complicated setup. Distorting commands from real humans should be more realistic and closer to reality than generating distorted commands in an autonomous fashion, however, this statement needs to be backed with experimentation as discussed in 6.3. RQ1.1 listed at the beginning of this chapter cannot be answered without methodical comparison between our approach and real data from children with accessibility needs.

Additionally, an AAN method using data modelling was presented. Various models were tested and there were some promising results from regression trees and GPR, with regression trees performing better than GPR on the dataset. This is likely due to memory limitations imposed by GPR as discussed earlier in the chapter. SVR did not seem to converge on a solution, and neural networks showed some promise, however, it seems more data is needed for it to converge. With reference to RQ1.2 presented at the beginning of this chapter, the AAN approach is promising and was able to learn from an expert providing feedback during teleoperation. However, no conclusions can be made as discussed in 5.2.7.

Overall, despite numerous challenges and limitations, the approaches presented in this chapter show potential to help designers account for upper limb mobility challenges. Additionally, the AAN approach has potential to create accessible play sessions without interfering with gameplay, if the supervisor (who provides assistance in the training phase) does not not interfere with gameplay when providing assistance.

Chapter 6

Conclusion and Future Work

6.1 Summary of Contributions

In this thesis, a new social robot for robot assisted play was presented. The robot, MyJay, was designed to encourage play interactions between children with physical special needs and their peers by enabling children to play a ball game through the robot. MyJay is able to pickup balls and throw them in the target goal, similar to a basketball game. The primary mode of interaction with MyJay is teleoperation, where a child can play the game by directly teleoperating MyJay.

The thesis attempted to answer the following research questions and sub-questions (which were also listed in the introduction and in relevant chapters):

- **RQ1:** How can we exploit robots to create joyful play sessions that facilitate human connection for children with different levels of physical abilities and needs?
  - **RQ1.1:** Can we simulate robot teleoperation difficulties that face individuals with special needs, specifically upper limb mobility challenges such as CP?
  - **RQ1.2:** Can we use expert feedback during teleoperation to build an adaptive assistive system that does not interfere with gameplay?
- **RQ2:** How can we involve children with physical special needs, specifically children with upper limb challenges, as part of the design process of inclusive robots for robot-assisted play?

RQ1 guided our design process, and the robot went through a few iterations. Due to the lack of in-person studies, it is not possible to provide a clear answer to the research question, however, a list of guidelines on designing accessible robots for children with different levels of physical abilities, were presented in 3.5.

With respect to RQ2, therapists as well as children with special needs and their families were consulted at various stages of the design process. This ensured the design is accessible and accommodates for the needs of children even though it was not possible to conduct in-person studies during COVID restrictions. Discussion on what worked well and what did not work, with regards to our interview approach, was provided in 4.4 along with lessons learned in 4.5.

With respect to the sub-questions presented in chapter 5, a novel method to simulate teleoperation difficulties that face individuals with special needs, specifically upper limb mobility challenges such as cerebral palsy. The method distorts healthy user input based on findings from literature and based on interviews conducted with children with special needs and their families (interview findings presented in chapter 4). In-person studies are required to answer RQ1.1, however, the approach seems to have lots of potential as a tool for developers of robotics technologies. To answer RQ1.2, an adaptive, assistance as needed (AAN) model was built from data collected while applying the distortion algorithm to input from healthy users. I acted as an "expert", correcting trajectories affected by the distortion algorithm in real-time. Multiple regression strategies were trained on the data and a comparison of performance was presented in 5.2.6.

6.2 Conclusion

MyJay features robust mechanisms and modular designs with 3D-printed functional parts allowing for quick modifications. All non 3D-printed parts were obtained commercially with little to no machining required. Based on interviews with children and their families, a custom joystick was designed to increase accessibility and reach a wider audience. Software packages for the robot are ROS compatible and follow standards that are widely used in the robotics community, increasing the potential of MyJay as a research robot. Special care was taken to ensure MyJay is aesthetically pleasing with a friendly look and bright colors. An LED strip was placed under the robot's shell for motion cues and enhanced communication, as well as displaying the robot's internal states.

To deal with COVID restrictions, a novel method to distort healthy user input was created to simulate the gameplay of individuals with upper limb mobility challenges. This was done by formulating a set of distortions based on consulting the literature and conducting user interviews. This approach could speed up development of accessible robotic applications in future projects and has potential beyond this project. To the best of our knowledge, the approach presented in this thesis has not been done before.

Finally, learning from demonstration was used to create an AAN model and proof of concept was demonstrated by constructing various models using different machine learning approaches. The regression tree AAN model was able to provide assistance during gameplay such that it does not provide too much assistance to the point where the game becomes too boring, nor does it allow the game to be too hard to the level of frustration. In-person experiments are needed to verify the model.

6.3 Limitations and Future Work

The main limitation on this project was the COVID restrictions which were imposed for the majority of the duration of the project. Most future work recommendations involve in-person studies that were still not possible at the time of writing this thesis. Another impact of COVID was the inability to hold in-person co-design group sessions, which was addressed by holding remote interviews with children with special needs and their families and using their feedback to improve the design. This does not substitute for co-design sessions and resulted in a serious missed opportunity to include children in early stages of the design process.

Given the successful design and construction of MyJay, there is much room for future work. Due to COVID limitations, the robot was not validated with children with accessibility needs, and this should be done as soon as possible to check if it accounts for their needs, and whether it needs a redesign. Once a small scale study is done, a long term "in the wild" study should take place where the robot is tested at a school or a community center. This will show whether the design has potential for long-term use, and point out any issues that did not come up during in-lab testing.

An important piece of work is verifying the teleoperation distortion module. This can be done in parallel to the work mentioned above or even on a robot other than MyJay. The module can be verified by comparing its output to teleoperation data from children with upper limb mobility challenges.

Another important future direction is improving the *assistance as needed* model by collecting data from studies with children with special needs and training a model or a few models on the collected data. After, it can be verified in a separate study and compared to “no assistance” and “always on assistance” conditions to check its effectiveness and impact on gameplay.

There are some secondary future works that can improve MyJay as a social robot. First, interaction can be improved by adding sound cues and testing their effectiveness experimentally. MyJay’s design is a mix of abstract and animal-like design, and that should be taken into account when designing sound cues for it. Second, the robot should be modelled in Gazebo [1] to enable quick development of algorithms and testing without having to use the robot. This is especially useful for testing machine learning algorithms such as the *assistance as needed* module. Third, the code should be made more efficient so that it uses less computing resources. Currently, the compute module overheats when running all programs at the same time. Lastly, MyJay can be redesigned and be made lighter and cheaper to construct. The redesign should not happen before testing the robot experimentally with children with accessibility needs to identify any current limitations in the design. MyJay’s interface (the custom joystick), may need a redesign as it was built based on literature and interview feedback. It would be beneficial to have a co-design study with children with various types of challenges to ensure they are involved in the design process for the interface, which is quite important because the interface has an effect on enjoyment of the teleoperation experience.

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[1] http://gazebosim.org/

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APPENDICES

Appendix A

Useful information for building your own MyJay

Link to Github repository housing code and CAD files for the robot:
https://github.com/hamzaMahdi/myjay-bot.git

Table A.1: Bill of materials required to build MyJay

Retailer	**Part**	**SKU**	**Amount**	**Unit Price (USD)**
GoBilda	**Motion**			
	Drivetrain kit	3209-0001-0001	1	379.99
	Mecanum wheel set	3213-3606-0001	1	129.99
	Intake+Elevator Motors	5202-0002-0019	2	39.99
	Backup motor (high rpm)	5202-0002-0003	1	39.99
	Bevel gear set	3204-0002-0001	2	24.99
	100 mm D shaft	2101-0006-0100	6	2.39
	144 mm, 12 mm diameter REX shaft	2104-0012-0144	3	2.29
	12 mm shaft collar	2910-1026-4012	6	2.59
	6 mm shaft collar (2 pack)	2910-0816-0006	2	3.99
	Hyperhub (6mm)	1310-0016-1006	2	5.99
	1611 Series Flanged Ball Bearing - 6mm ID x 14mm OD, 5mm Thickness	1611-0514-0006	2	2.99

	1611 Series Flanged Ball Bearing - 8mm ID x 14mm OD, 5mm Thickness	1611-0514-0008	1	2.99
	Structure			
	Low profile C-Channel	1121-0015-0384	1	11.29
	Side C-Channel (11 hole)	1120-0011-0288	2	9.99
	Side C-Channel (9 hole)	1120-0009-0240	3	8.39
	Quad block pattern mount	1201-0043-0002	8	5.99
	Side C-Channel (2 hole)	1120-0002-0072	2	2.79
	Electronics and Wiring			
	Grommets	2911-0014-0001	1	1.99
	300 mm, 3.5 mm bullet connector wiring	3800-0013-0300	6	1.99
	Encoder breakout	3801-0919-0300	2	3.99
	RoboClaw 2x7A Motor Controller	IMC404	3	79.99
	Standoffs			
	18mm Standoff	1501-0006-0180	1	1.89
	24mm Standoff	1501-0006-0240	1	2.19
	46mm Standoff	1501-0006-0460	1	3.29
	16mm Standoff	1501-0006-0160	1	1.79
AndyMark	1/2 in. Hex ID Shielded Flanged Bearing	am-2986	2	6
	3 in. Compliant Wheels	am-3946	1	7
	1/2 in. Steel Hex Shaft Stock	am-0856	1	6
McmasterCarr	Linear Motion Shaft (400 mm length, 8 mm diameter)	6112K45	1	14.35
Hobby King	5000mAh 3S 30C Lipo Pack	9067000278-0	1	36.6
Blue Robotics	Basic ESC	BESC30-R3	1	27
	Lithium Battery Charger	BATTERY-CHARGER-0620AC-US-R1	1	149

Amazon	Brushless Motor 6354-270KV	Alomejorwu782f3di6	1	75.84
	Nvidia Jetson Nano	102110417CF	1	126.7
	Arduino Nano	A000005	1	20.9
	Misc 3D printing filaments			∼200
	GeeekPi AC8265 Wireless NIC Module for Jetson Nano	L-0031	1	26.27
	Raspberry Pi Official Camera Module V2	113990214C	1	29.48
Toronto Gear	36 teeth timing pulley	36-5M09M6A10	1	20
	68 teeth timing belt	340-5M-09	1	7.35
Aliexpress	GT2 20 Teeth Timing Pulley, 6 mm bore	N/A	2	3.99
	GT2 Timing Pulley 30 Tooth, 12 mm bore	N/A	1	0.96
	GT2 68 Tooth timing belt (136 mm length)	N/A	1	6.99
	GT2 60 Tooth timing belt (120 mm length)	N/A	1	6.99

Table A.2: Pulleys on MyJay's subsystems and their respective setup

Sub-system	**Type**	**Driven pulley teeth #**	**Driving pulley teeth #**	**Belt teeth #**
Intake	GT2	50 (3D printed)	20	136
Elevator	GT2	30	20	120
Flywheel	GT5	38	36	340

Appendix B

Therapist Survey Questionnaire

This is a survey used to get feedback from therapists. The study involving the survey is on-going at the time of writing this thesis.

Intro

Thank you for your interest in our study. This form will inform you about the details of the study and ask you a few open ended questions.

Before getting started, we ask you to carefully read the following information form. If you have any questions feel free to contact the researchers at: hmahdi@uwaterloo.ca

SIRRL
Social and
Intelligent
Robotics
Research
Laboratory

Consent

By signing this consent form, you are not waiving your legal rights or releasing the investigator(s) or involved institution(s) from their legal and professional responsibilities.

I have read the information letter concerning the research project entitled Consulting Therapists on Accessible Robot Design conducted by Hamza Mahdi of the Department of Electrical and Computer Engineering at the University of Waterloo. I have had the opportunity to ask any questions and receive any additional details I wanted about the study.

I acknowledge that all information gathered on this project will be used for research purposes only and will be considered confidential. I am aware that permission may be withdrawn at any time without penalty by advising the researchers.

I understand that all of my answers are anonymized and some my be published in scientific publications.

This study has been reviewed and received ethics clearance through a University of Waterloo Research Ethics Committee (ORE# - 42743). If you have questions for the Committee contact the Office of Research Ethics, at 1-519-888-4567 ext. 36005 or ore-ceo@uwaterloo.ca.

For all other questions contact Hamza Mahdi at hmahdi@uwaterloo.ca. Additionally, you may contact the principal investigator, Dr. Kerstin Dautenhahn at kerstin.dautenhahn@uwaterloo.ca

I understand that I can only continue with the study after I give consent.

○ I agree

○ I disagree

Video

Please watch the below video carefully:

MyJay

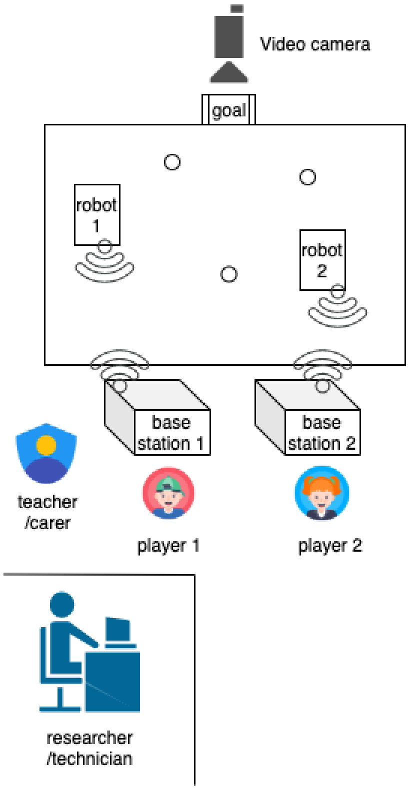
Click next to proceed to the questions. They should not take more than 15 minutes.

Questions

What is your first impression on the robot/its abilities?

This robot is intended to play a ball game where it picks up balls and throws them in a goal area, similar to basketball. The robot can either think and move on its own, or you the child controls how it moves. The robot will always wait for the child to tell it what to do next. Do you think this could be a fun activity?

Here is a sample setup where two children are controlling one robot each:



What are your thoughts on the game/robot in terms of each child controlling a robot vs two children controlling/playing a single robot (ex: one child controls movements and the other controls shooting the ball)

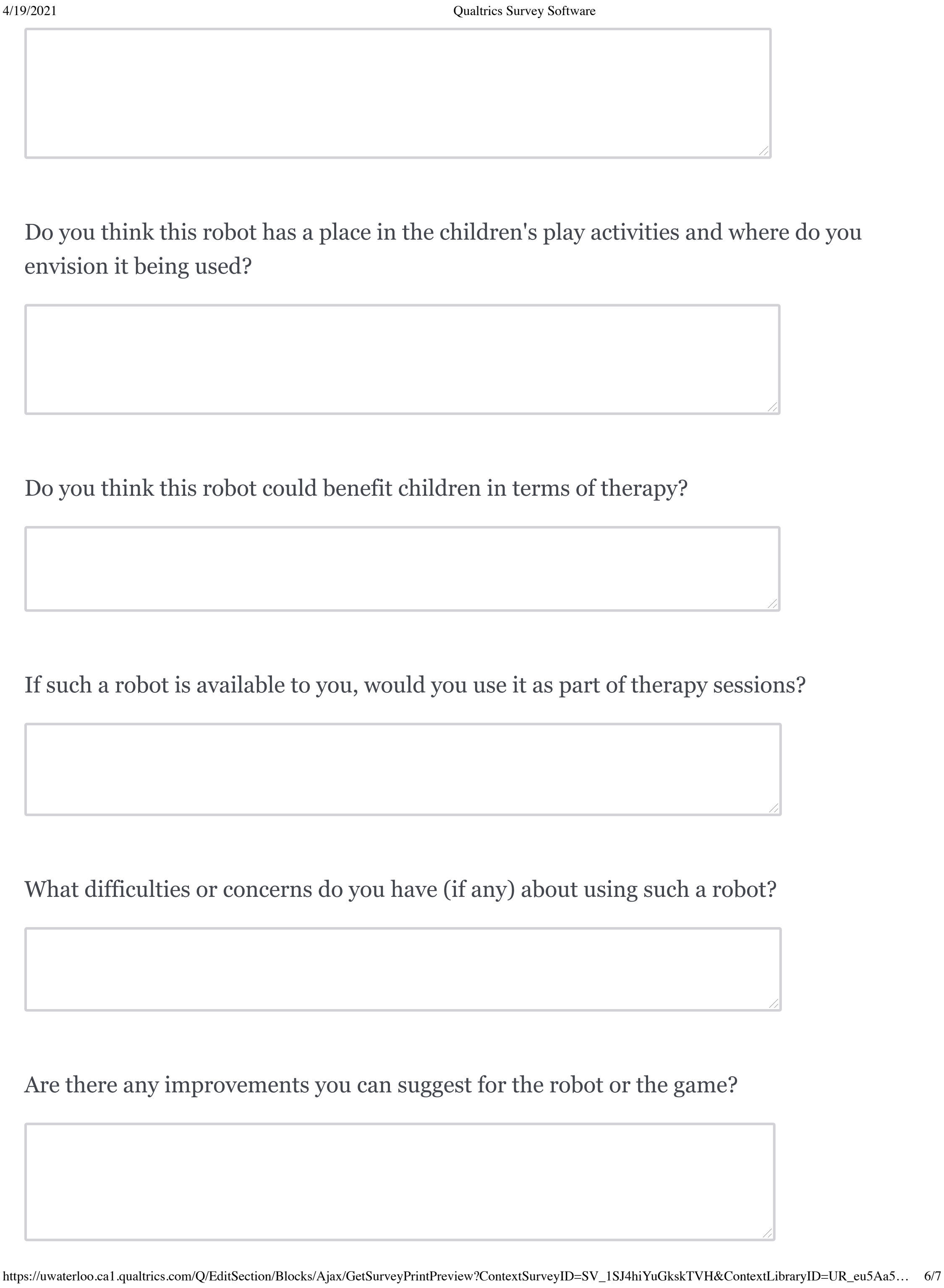
What sort of accessibility needs do the children you work with have?

What barriers to play do children you work with have?

Compared to their peers, what are their play habits?

Do they play video games and if so, what sort of controllers/joystick do they use as input?

What are your thoughts on the lights and light patterns shown in the video and do you have any recommendations/improvements to suggest?



Do you think this robot has a place in the children's play activities and where do you envision it being used?

Do you think this robot could benefit children in terms of therapy?

If such a robot is available to you, would you use it as part of therapy sessions?

What difficulties or concerns do you have (if any) about using such a robot?

Are there any improvements you can suggest for the robot or the game?

Can we contact you for further questions via email?

○ Yes

○ No

Email

Please provide your email address:

Feedback

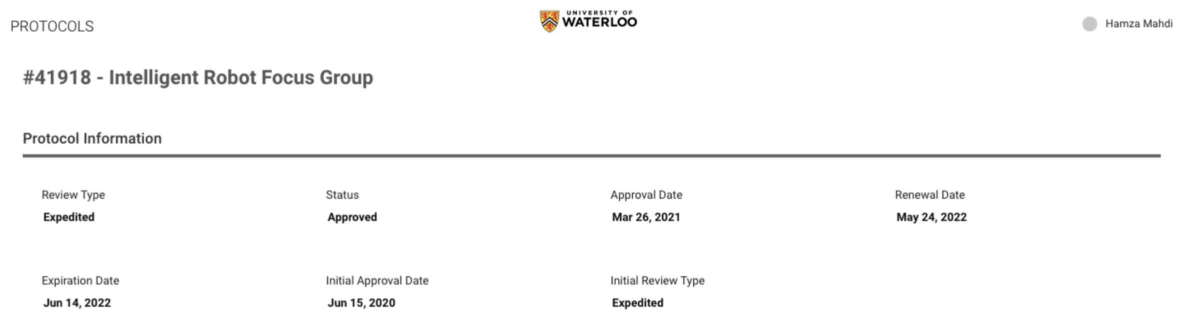
Thank you for your participation. Your input is invaluable in the process of designing the robot. Here is a feedback letter that includes more information about the study and a relevant reference. The robot design will be made open-source free of charge near the end of the design cycle.

Powered by Qualtrics

Appendix C

Ethics Approvals

The following are approvals received from the safety office for various studies conducted (or were planned but blocked due to COVID) during this thesis project.



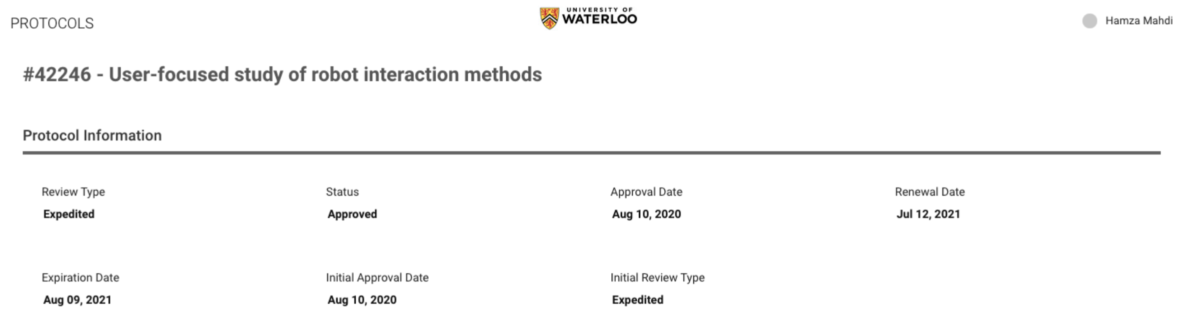
PROTOCOLS

Hamza Mahdi

#41918 - Intelligent Robot Focus Group

Protocol Information

Review Type **Expedited**	Status **Approved**	Approval Date **Mar 26, 2021**	Renewal Date **May 24, 2022**
Expiration Date **Jun 14, 2022**	Initial Approval Date **Jun 15, 2020**	Initial Review Type **Expedited**	



#42246 - User-focused study of robot interaction methods

Protocol Information

Review Type	Status	Approval Date	Renewal Date
Expedited	**Approved**	**Aug 10, 2020**	**Jul 12, 2021**
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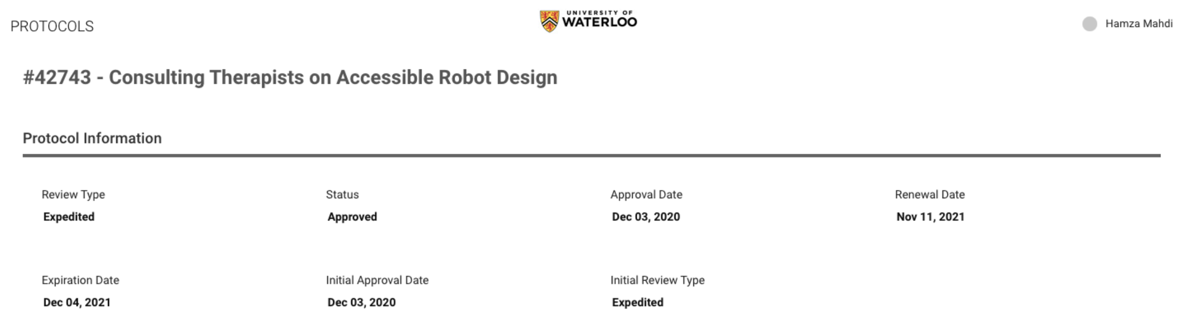
Aug 09, 2021	**Aug 10, 2020**	**Expedited**	



PROTOCOLS

UNIVERSITY OF WATERLOO

Hamza Mahdi

#42743 - Consulting Therapists on Accessible Robot Design

Protocol Information

Review Type	Status	Approval Date	Renewal Date
Expedited	**Approved**	**Dec 03, 2020**	**Nov 11, 2021**
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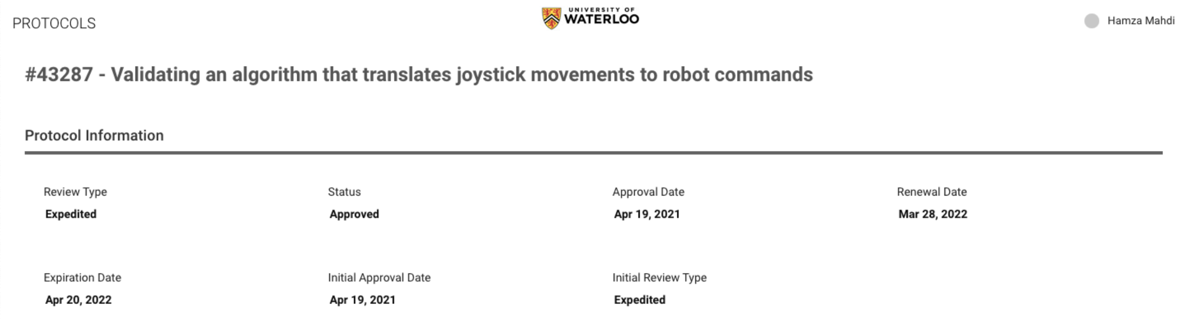
Dec 04, 2021	**Dec 03, 2020**	**Expedited**	



#43287 - Validating an algorithm that translates joystick movements to robot commands

Protocol Information

Review Type	Status	Approval Date	Renewal Date
Expedited	**Approved**	**Apr 19, 2021**	**Mar 28, 2022**
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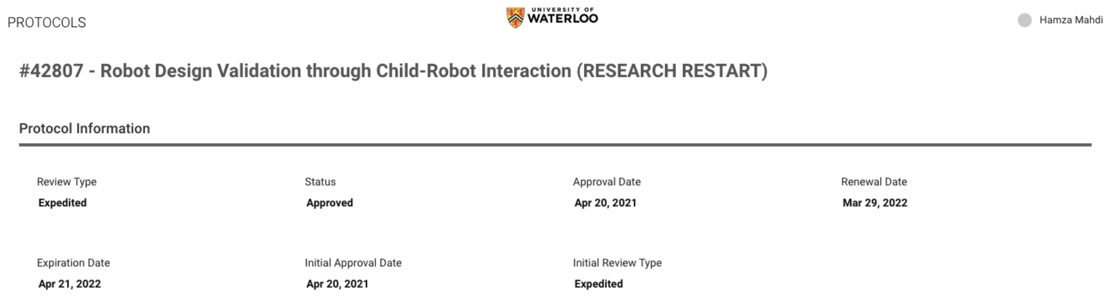
Apr 20, 2022	**Apr 19, 2021**	**Expedited**	



PROTOCOLS

Hamza Mahdi

#42807 - Robot Design Validation through Child-Robot Interaction (RESEARCH RESTART)

Protocol Information

Review Type **Expedited**	Status **Approved**	Approval Date **Apr 20, 2021**	Renewal Date **Mar 29, 2022**
Expiration Date **Apr 21, 2022**	Initial Approval Date **Apr 20, 2021**	Initial Review Type **Expedited**	