A Low-cost Social Companion Robot for Children with Autism Spectrum Disorder

By

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Abstract

Robot assisted therapy is becoming increasingly popular. Research has proven it can be of benefit to persons dealing with a variety of disorders, such as Autism Spectrum Disorder (ASD), Attention Deficit Hyperactivity Disorder (ADHD**),** and it can also provide a source of emotional support e.g. to persons living in seniors' residences. The advancement in technology and a decrease in cost of products related to consumer electronics, computing and communication has enabled the development of more advanced social robots at a lower cost. This brings us closer to developing such tools at a price that makes them affordable to lower income individuals and families. Currently, in several cases, intensive treatment for patients with certain disorders (to the level of becoming effective) is practically not possible through the public health system due to resource limitations and a large existing backlog. Pursuing treatment through the private sector is expensive and unattainable for those with a lower income, placing them at a disadvantage. Design and effective integration of technology, such as using social robots in treatment, reduces the cost considerably, potentially making it financially accessible to lower income individuals and families in need. The Objective of the research reported in this manuscript is to design and implement a social robot that meets the low-cost criteria, while also containing the required functions to support children with ASD. The design considered contains knowledge acquired in the past through research involving the use of various types of technology for the treatment of mental and/or emotional disabilities.

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List of Acronyms

$CAD – Canadian Dollar

$USD – United State of America Dollar

3D – Three Dimension

ACL – Alexa Communication Library

ADD – Attention Deficit Disorder

ADHD – Attention Deficit Hyperactivity Disorder.

ADSL – Alexa Directive Sequencer Library

AED – Amazon Echo Dot

AFML – Alexa Focus Manager Library

AIP – Audio Input Processor

ALSA – Advanced Linux Sound Architecture

API – Application Program Interface

API – Application Programme Interface

ASD – Autism Spectrum Disorder

ASP – Audio Signal Processor

AURORA – Autonomous Robotic Platform as a Remedial tool for Children with Autism

AVS – Alexa Voice Service

CA – Capability Agents

CAI – Computer Assisted Instruction

CDCP – Centre for Disease Control and Prevention

CHARLIE – Child Centered Adaptive Robot for Learning in an Interactive Environment

CHEO – Children's Hospital of Eastern Ontario

CHRI – Child-Robot Interaction

CMA – Canadian Medical Association

CPU – Central Procession Unit

DC – Direct Current

EBPS - Evidence-Based Practices

EEG – Electroencephalogram

GPIO - General-Purpose Input/Output

GUI – Graphic User Interface

IC – Integrated Circuit

IPA – Intelligent Personal Assistant

KASPAR - Kinesics and Synchronization in Personal Assistant Robotics

LED – Light Emitting Diodes

NASS – National Autism Spectrum Disorder Surveillance System

NIMH – Nikel Metal Hydride

NPDC – The National Professional Development Centre on ASD

OAC – Ontario Autism Coalition

OCTC – Ottawa Children's Treatment Centre

ONTABA – Ontario Association for Behavior Analysis

OS – Operating System

PCB – Printed Circuit Board

Pigpiod – Pigpio Daemon

PIR – Passive Infrared

PWM – Pulse width Modulation

RAT – Robot Assisted therapy

RPi – RaspberryPi

SAR – Socially Assistive Robots

SDK – Software Development Kit

SDS – Shared Data Stream

Secure Shell - SSH

STEM – Science, Technology, Engineering and Mathematics

TAII – Technology-aided Instruction and Intervention

USB – Universal Serial Bus

VUI – Voice User Interface

WIFI – Wireless Fidelity

WWE – Wake Word Engine

Chapter 1: Introduction

Autism Spectrum Disorder (ASD) is a developmental disability. Individuals suffering from ASD experience dysfunctionality on several aspects including: social skills, verbal and nonverbal communication, tolerance to high volume sounds and auditory background "noise", and difficulty dealing with deviations from expectation. Those with this disability often have repetitive behaviours and unusual interests [1]. ASD affects people in varying ways, degrees, and forms. Different people suffering from ASD tend to have different experiences with autism, as symptoms form a spectrum with the severity of each symptom varying from one person to another. Each person with ASD has his/her own unique challenges as well as strengths which define the kind of support they need to lead a fulfilling life [2].

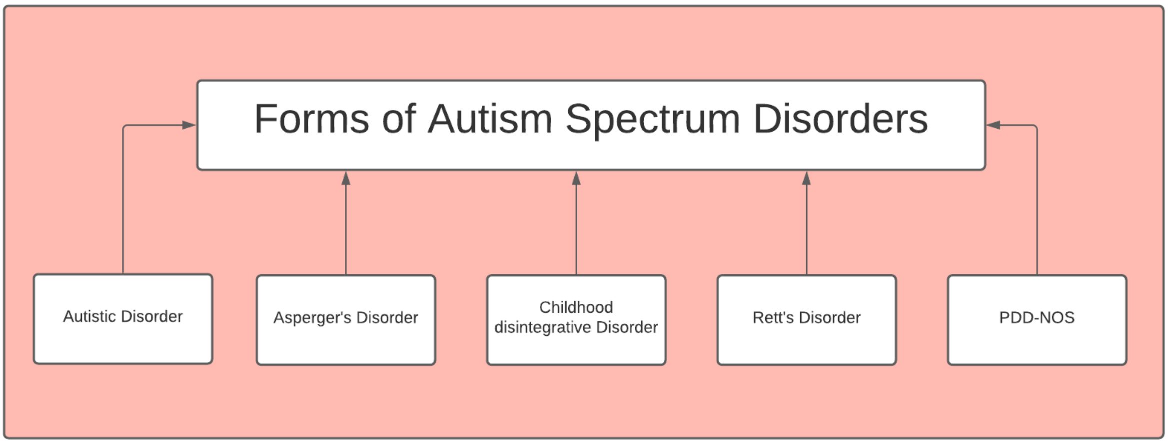


Figure 1.1: The five major forms of pervasive developmental disorders in the Autism Spectrum [1] (Image created by Author).

Some children affected with ASD can have relatively good verbal skills and only a minor language delay but considerably impaired social skills, whereas some other children could be lacking nonverbal skills, and the ability or interest to communicate or socialize with people they are not familiar with. A child or adult with ASD may not engage in "play" or "pretend" games (e.g. pretend to "feed" a doll, act or speak to something in real life when in fact it is not), may not wish to interact with people, and be unaware of how to speak to, engage, play, and connect with things around them. Currently, no medical test exists for ASD. Diagnosis is made typically after careful assessment and observation. Such process might include clinical observations, parent interviews, and possibly the use of one or more alternative autism diagnostic tests including using robotics [1]. In recent years, intervention methods for ASD have been developed, however, it is difficult to identify a single approach that would be applicable to every individual with ASD. This is because many of these intervention methods lack sound evidence regarding their effectiveness due to the large heterogeneity of the autism spectrum. Recent advances in technology could be seen to offer a promising opportunity for innovation in the intervention and diagnosis of autism spectrum disorder, especially in the area of robotics, seeing that robots can be used as social interactive partners [2].

Robotics offers a tremendous opportunity for innovation in the study of human social behavior. Using controlled stimuli allows us to focus on a single phenomena and obtain a qualitative analysis, including the use of robots during therapy sessions for the treatment and education of people with ASD [3]. Robots can act as support for children with ASD who show clear attraction towards them. Other technological systems with enhanced systemizing voice interaction skills, such as Amazon Alexa, can also be useful in the development of a robot. Robots can be applied in several support practices categorized into three areas: (a) a child's behavior; (b) human vs robots' behavior; (c) to establish evidence and provide feedback on performance. A robot provides feedback to the child about his/her current activity as well as reinforcing his/her learning. Also, the robot can help therapists to achieve more natural interaction with the child or adult, increasing the therapist's ability to individualize the nature of the therapy sessions. Robots can be used to model, teach, and practice skills which aim to improve the child's social interaction skills with others [2].

Rapid progress in the field of technology has also seen the introduction of a new interaction paradigm that is gradually integrating itself in everyday life. Some examples of these technologies are voice-controlled, intelligent personal assistants such as Amazon Echo [3] and Google Home [4]. These assistive technologies combine speech, images, and animation in interactive ways to structure concepts that suit the learner's level of understanding as well as their interests. They offer strong potential for creating inclusive, accessible, and meaningful interaction [4]. Robot-assisted therapy is generating a lot of attention in the therapeutic and teaching environment for learning social skills. Robots are trailed or integrated into therapy by different professionals to assist children with ASD [5].

For instance, during their studies, Boccanfuso & O'Kane observed that using robots as a social mediator in interaction with children with autism actively bolstered their desire to learn convenient and adaptable social and communication behaviors [6]. According to Cabibihan, Javed, Ang, & Aljunied, robots used in ASD applications can be divided into two categories: structured and unstructured. Structured application of robots in autism spectrum disorder encourages children to actively explore and navigate their environment through independent play activities with robots, while the unstructured approach consists of a joint participation in therapeutic activities between children with autism, a robot, and a therapist [7]. Modern technology has seen many robots developed as an assistive social tool for people living with ASD in therapeutic applications This will be further discussed in Chapter 2: Literature Review. With voice-controlled, intelligent personal assistants (IPAs) we can implement speech input and output and overcome the limitations text dictation and screen reader software have. The Amazon Echo Dot (AED) speaker, which connects via the internet and uses the voice-controlled Alexa voice service software (AVS) to communicate and interact with users, presents an opportunity to redefine the way humans can interact with technology. Integration of general purpose IPAs, such as the Amazon Alexa, are capable of simulating "intelligent" verbal interaction with humans, which opens the opportunity of materializing new tools that can be used in speech therapy, learning support, and training in social behavior and interaction, all of which are critical for people with ASD [4].

1.1 Research Motivation

Autism spectrum disorder manifests itself as a group of a multitude of closely related behavioral deficiencies. Individuals in the autism spectrum might have difficulties with socially interacting and communicating, learning, exploring their environment, and expressing empathy; they might also demonstrate inflexible behavior. It should be noted that the presence of a few autism-like symptoms does not mean the person has ASD. When it comes to their behavior and abilities, two children diagnosed with ASD may have significantly different behavioral and skill characteristics. Generally speaking, children with ASD may struggle with social behavior and understanding, speech and language, have restricted patterns of behavior and play, appear clumsy, be fascinated by moving pieces, wish to perform repetitive tasks (e.g. turning a light-switch on-off), and repeat the same sentences or discuss the same subject over and over again. The National Autism Spectrum Disorder Surveillance System (NASS) (2018) reported that an estimated 1 in 66 (15.2 per 1,000) children and youth (5-17 years) are diagnosed with ASD in Canada. Compared to females, males were diagnosed with ASD four times more often, that is 1 in 165 females and 1 in 42 males [8]. In 2012, The Centre for Disease Control and Prevention (CDCP) in the United States reported that an estimated 1 in 88 children were diagnosed with ASD in 2012 [9].

For many families, having a child with ASD can be challenging. Coping with the additional stressors, such as off task behavior, communication barrier, and loss of interest can have an emotional and physical impact on the family [10]. Depending on the symptoms and severity, diagnosing and evaluating a child with ASD is not a quick process because there is no single medical examination that is proven to be definitive [11]. Several diagnostic sessions might be required, followed by lengthy treatments of a multitude of disabilities, including behavioral, speech, and learning [12]. Frequent hospital visits can be difficult for children with ASD as the sights, sounds, and smells can contribute to sensory overload [13].

Caring for a child with ASD can also have a significant financial impact on the parents. The cost of support and care, including out of pocket expenses for every child and individual living with ASD per month in Canada, is estimated at a weekly cost of $1,325 Canadian dollars [14]. Jarbrink et. al. [15] conducted a diary survey to measure the informal care time parents dedicated to their autistic child. The results showed that on average, children with ASD received approximately 60 hours a week of care and support from their parents, and the parents an approximated 17-22 hours per week that they would have spent on other activities such as voluntary or unpaid employment [15]. Further research by Virginie et. al. provides useful information on the unmet needs of families of children with ASD, and the results show that families struggle with social activity needs (78.2%), the lack of information about available services (77.2%), and provision of continuous service (74.3%) [16].

The table below provides an estimated annual cost of the care of a child with ASD in relation to the level of severity [14].

CHILD	LEVEL OF SEVERITY WITH ASD	ESTIMATED COST (CAD $)
Child A	Severely affected; requires support and care 24 hours per day, seven days per week.	$131,893 PER YEAR
Child B	Moderately affected, verbal; frequently finds it difficult to use words correctly and is unable to express themselves appropriately.	$74,626 PER YEAR
Child C	Diagnosed with sensory challenges (noise sensitivity, wears headphones); academically smart but lacks basic understanding of social standards.	$26,639 PER YEAR

Table 1.1: Cost estimate for caring and supporting a child with ASD depending on their level of severity [9].

To pay for lifelong care for an autistic child like child A for instance, the estimated cost could rise to $158,000 per year and this could mean that the family's annual income needs to be over $200,000 to meet basic care/support needs. Approximately only 10 percent of Canadian adults who work full time can earn such an income to support their dependents who have no disabilities. This has left many Canadian families with autistic children at a disadvantage. They somehow must juggle through different ways to help care for and support their children. This also leads to a greater risk of families experiencing poverty or material hardship [14]. As a result of the high cost of care, many children diagnosed with ASD do not receive proper care. Recently, however, growing evidence has suggested that robot assisted therapy can help to reduce the financial burden associated with caring for a child with ASD [17]. Integrating a robot as part of a therapy session can improve its ability to gather relevant data and information through various means such as detecting facial expressions, gestures, body motion, and verbal cues [18]. Children with ASD enjoy playing with interacting robots, which have the potential to provide a safe and distraction free environment for the children to interact and communicate, thereby helping them develop their social skills [19]. The Amazon Echo Dot voice-controlled assistant device presents a very interesting application that provides a conversational interface which allows users to ask for, receive and save information from the comfort of their home. Users can seamlessly execute simple everyday tasks through the voice input and output interface, such as playing music and getting live news and weather reports. This research work is set out to potentially study how children affected by autism would engage with a social device that utilizes Amazon Alexa's voice assistant. This would allow the device to physically animate parts of its body as well as respond to simple tasks and commands. Although this deviates from the standard design of robots, it indicates that simple actions or tasks can have a significant impact if they can produce the intended response.

1.2 Problem Statement

Autistic children struggle greatly with self-expression and turn taking, including when their attention is divided, while playing, imitating, and socializing with their environment [20]. The following statistics were obtained from a survey conducted by the Ontario Autism Coalition (OAC) in 2019 which received 1590 responses:

- The prevalence rate shows that autism affects 1 in 66 children in Canada.
- Approximately 40,000 children in Ontario have been diagnosed with ASD.
- 23,000 children are on waitlist to receive treatment.
- Hourly set amount of money offered by the government to parents to hire and pay professionals is $55.

Early diagnosis is key for treatment and diagnosis of ASD. Robots are being used to teach social interaction and communication skills as part of therapeutic intervention, but there is more room for development [20]. Recently, at the Children's Hospital of Eastern Ontario (CHEO), Professor Lundy Lewis, an academic and researcher in artificial intelligence and human-robot interaction, tested five (5) technological social robots during a therapy session with six-year-old children with autism spectrum disorder. The robots were JIBO, PARO, Joy-for-all cat, Joy-for-all puppy, and an Amazon Echo speaker stuffed into an ordinary animal toy [21]. Among the five robots, four of them were social robots i.e. JIBO, PARO, Joy-for-all cat, and Joy-for-all puppy. Unlike the Amazon Echo Dot speaker stuffed inside the animal toy, the other four social robots were all Animanoid and could physically animate when performing tasks as commanded. It was also noted that only JIBO and the Amazon Echo Dot speaker toy had voice-controlled technology features.

Figure 1.2: Experiment setup performed by Prof. Lundy Lewis with five social robots (PARO, JIBO, Joy for all cat and puppy and Amazon Echo in an ordinary toy) to determine which robot a child with ASD feel socially connected with. [22] (copyright permission obtained)

Professor Lundy Lewis discovered that the technological design features of the five social robots impacted how the children interacted with the robots individually [22]. He particularly noticed that the children actively engaged with the four social robots JIBO, PARO, Joy-for-all cat, and Joy-for-all puppy, but the children did not actively socialize and engage with the Amazon Echo Dot speaker that was stuffed inside the ordinary animal toy. This was not a surprise because according to Sarah Shultz et al, children with autism are attracted to physical objects and their attention increases when the object moves [23]. It was therefore evident that although the animal toy with an Echo Dot speaker placed inside it had some interesting features such as voice-controlled technology to respond to questions and provide answers, it lacked some important features such as the ability to physically animate or move any parts of its body to gain the attention of the children. The work by Professor Lundy Lewis indicates a gap of knowledge in relation to the design of the robots used in his experiment during the therapy session with children with ASD, and the fact remains that the current price tag of assistive equipment for this method of treatment remains above what low-income families can afford [22].

Seeing that the children showed great interest towards the ordinary animal toy with an Amazon Echo Dot speaker even though it lacks many features present in the other four robots combined with the fact that the Amazon Echo Dot speaker only cost $49.99 CAD, presented an opportunity to explore low cost alternatives. Robotics design and voice-controlled technology can develop or enhance an affordable social interactive robot prototype for families with low income, which can form a vital part of the intervention, treatment and social skills development for children with autism.

Through research, it was discovered that the Lexa-Bear social robot was built to tackle the problem of cost for families who cannot afford to purchase expensive robots to support their children with autism. The Lexa-Bear robot also introduces some unique features, such as voice interaction using the Amazon Alexa voice service, which requires the presence and use of a Dot speaker. Independently, Prof. Lewis inserted the Echo Dot speaker in an ordinary toy by himself, thus creating his own version of the robot, and used it in his studies with children with ASD. However, purchasing of an Echo Dot is associated with a certain cost and the robot can only animate its mouth. Our work eliminates the need of an Echo Dot speaker device and can animate both mouth and hands, which will attract more attention and make the interaction more "natural". Eliminating the purchase of an Echo Dot speaker reduces the cost, which is a significant factor for low income families. We are confident that our work generated a social robot with enhanced features and lower cost. We expect it to become a valuable tool in the training of children with ASD, and if successful, it will greatly contribute and assist children with ASD to develop relevant social skills and meaningful connection with their environment.

1.3 Research Objectives and Contributions

Table 1.1 shows that the treatment and care for people living with autism and their families can be very expensive. Robot-assisted therapy is relatively new and is being used as a cheaper alternative to offset the high cost of treatment for children living with autism and it has become increasingly popular in recent years.

The key goal of this experimental research work is to develop an enhanced and affordable version of the Lexa-Bear social robot [24]. The idea is to give a child with autism the opportunity to interact with the social robot through voice communication which encourages the child to engage in social play (with the robot) as part of the therapy procedure.

Professor Lundy Lewis provided the specific set of functionalities and features that the robot should have. They are the product of his observations made during numerous treatment sessions he attended where social robots were used.

i. The robot must interact with the children by voice. This functionality will use Amazon Alexa's voice service technology.
ii. It must physically animate when asked a question and physically animate when providing answers and maybe animate spontaneously when not engaged with children.
iii. It must be self-contained, i.e. battery-operated without having to be plugged into an electric grid.
iv. It must be attractive to children.
v. It must be safe, i.e. no opportunities for pinched or burned fingers.
vi. It must be relatively durable.
vii. It must be affordable, say $150 or less.

The implementation and leading tasks that need to be performed to meet the objectives are as follows:

1. Integration of Amazon Alexa's voice service built-in IoT design using a microcontroller for voice interaction and communication.
2. Design and implementation of a system to synchronize sound and animatronics.
3. Implementation of a device state and attention algorithm.

To achieve our objectives, the following contributions were made:

a) We designed a social interactive robot using off-the-shelf low-cost materials such a Teddy Bear, RaspberryPi, Amazon Alexa's voice service, PIR motion sensor, actuators, microphone, and speaker.

b) We implemented RaspberryPi as the central processing unit of our prototype. This is to control and interconnect the hardware devices and software packages.

c) We integrated the Amazon Alexa's voice service device SDK algorithm [25] in design so as to materialize voice command and communication.

d) We developed and implemented a design that integrates animatronics and motion using the AVS audio server, actuators (DC and servo motors), and software packages such as Pulse Audio, and Pacat, so that our robot can physically animate part of its body (mouth and arms) in real time, while listening and responding to voice command and communication.

e) We designed a device state and attention model. This technology enables the robot to be aware of the presence of somebody in the surrounding environment, and when presence is detected, the robot's arm is triggered automatically in order to attract the attention of the person and encourage interaction. It uses a PIR sensor and two servo motors. The robot becomes idle at the end of every interaction, but it does not go into an inactive state; it maintains awareness of its environment.

We expect that these technical features that the robot possesses, and its affordability will enable its adoption on a wider scale. In the future, we expect that therapists will conduct sessions online, making use of the social robot located in the premises of the patient. Going further they might conduct sessions involving several patients simultaneously, with each patient having his/her own robot, and they might even use the session to engage patients to interact jointly with the robot(s). Currently, training for parents or guardians of children with ASD is offered regularly by major hospitals and medical health institutions (e.g. The Children's Hospital of Eastern Ontario (CHEO), Ottawa Children's Treatment Centre (OCTC)), enabling them to become actively involved in the support and training of their child. Similar training can become available, which involves the use of a social robot, and/or integrated with parents in online treatment sessions. It should be pointed out that this will be immensely useful for children with ASD in developing countries, where the lack of finances and experts in the field tend to be significant compared to those in developed countries.

1.4 Thesis Outline

This thesis consists of six chapters including conclusion and future work. Chapter 2 presents a literature review on social robots used in therapy for children with autism. Various aspects of the robots are looked at, including the complexity of its build, the cost, and the results reported by the researchers who used them in actual treatment sessions. Chapter 3 explores our cost effective and affordable approach to enhance the existing design of the Lexa-Bear robot [26] so as to imitate the features and functions that currently exists in more expensive robots. We also introduce several new functions that do not exist in Lexa-Bear and present a case study of our design and compare it to existing designs to validate our work. Chapter 4 presents the evaluation of our robot in the form of test interactions and looks at their results. Chapter 5 concludes this work and discusses future research.

Chapter 2: Literature Review

2.1 Overview of Autism Spectrum Disorder (ASD)

Autism is a developmental disorder that affects the behavior and communication of children and adults. For people living with ASD, it is difficult to communicate their personal feelings or interact effectively. A high percentage of ASD patients exhibit repetitive behavior, such as repeating movements and words back and forth during a conversation, inability to focus or make eye contact with people, and showing less interest in socializing or participating in a reciprocal play activity with other individuals. Symptoms of ASD usually appear during the early years [27], very frequently between the age of 2 and 3. Parents tend to treat their child with ASD the same way they treat their other children, ignoring the child’s potential challenges, such as behavioral, learning, and sensory challenges, which makes the relationship difficult and further hampers the child’s emotional and intellectual growth. Children with ASD frequently face difficulty when forming friendships with peers and adapting to change, and their tendency to avoid interacting with the world and isolate themselves might lead to tantrums. Many of these children are hypersensitive to sounds and have difficulty concentrating on verbal communication if there is background noise, such as during classroom learning. The children frequently exhibit a short attention span because of their underlying conditions, which is why it is common for children with ASD to be diagnosed as having Attention Deficit Disorder (ADD) [28]. They might also have difficulties balancing themselves because of their sensory deficiencies. Families with children on the spectrum tend to be under significantly heavier stress. This applies to parents, siblings, and the child with ASD. Parents are a powerful force behind the significant efforts made in recent years to raise public awareness and demand stronger support from the government for treatment, research, and assistance for families with low income [29]. Studies have proven that early intervention is very important to the treatment of children with ASD including treating behavioural challenges

[30]. To facilitate faster and more efficient identification of ASD symptoms and treatment, there is a need for more innovation in diagnosis and treatment [31].

Research has shown that children with ASD prefer physical objects over people; they like to play with toys rather than other children [32]. Researchers have been exploring numerous ways to support and improve the lifestyle of children with ASD [33]. Like many other therapy methods, robot assisted therapy offers tremendous opportunity for innovation in diagnosing and treating the core social challenges faced by children with ASD. It has been explored in various settings to help children with ASD with learning social interaction and skills, as well as assisting with psychological and underlying physiological needs [31]. For example, many of these robots appear in the form of a ‘toy’[34]. The robot’s ability to help children sets it apart from regular toys [35]. Robots assisted therapy (RAT) has contributed significantly with the development of skills such as communication and social skills among people with ASD [36], RAT has also encouraged interaction, cooperation, and social play [37], as well as the management of facial expressions [38], all of which are significant skills for people living with ASD. This therapy method has also proven that it can encourage and help people with ASD to develop prolonged eye contact and hold their attention for an extended period of time [39]. The use of robots in ASD therapy has the potential to ease the pressure on parents and caregivers while maintaining a safe and predictable environment free of distractions. This also reduces anxiety for children, as they freely explore interaction and communication [40]. Further evidence also suggests that children with autism like to engage and play with humanoid devices over other robotic devices due to their simple appearance and predictable behaviors such as the ability to ask and provide answers to simple questions [41]. However, a study conducted by Warren et. al. using the NAO robot and an eye tracking device, showed that the level of attention and engagement between a robot and the child with ASD can decrease when they are exposed to the robot over a longer period due to sensory over stimulation [42]. This is because children with ASD get bored easily, or become overwhelmed when exposed to too much information, noise, or stimuli. This observation led researchers and designers of social robots to add extra features to robots, such moving body parts and eyes, so that the robot can act as a human teacher or companion in therapy and somewhat serve or assist children with ASD to participate in play activities that they find enjoyable while also supporting their learning and building their skills [43].

2.2 Current Support Strategies for Autism Spectrum Disorder

The 5th edition of the Diagnostic and Statistical Manual of Mental Disorder (DMS-5), defined autism as a family of disorders that affects children and adults. Many persons affected by autism tend to have regular speech, but they tend to have difficulties with the social aspect of their lives. This causes developmental abnormalities, which leads to deficiencies in social communication and interaction, repetitive and restricted patterns of behavior, and uncommon interests and activities which would persist throughout their life if no intervention treatment occurs.

According to the Centre for Disease Control and Prevention (CDCP) [9], Children with autism might display the following:

- They refuse to point to objects and show no interest in environmental stimulants that would attract the attention of normal subjects (e.g. the view or sound of an airplane flying).
- They refuse to look at objects when they are asked to.
- They prefer to be alone and avoid eye contact.
- They are disinterested in socializing with peers and others and have difficulty with sharing their interests and feelings with others.
- They might respond to sounds and can appear to be unaware of people or things around them.

These deficits significantly affect the ability of children with ASD to perform basic functions, such as going outside of the house and staying safe and joining social activities with peers at school or siblings at home. However, an increasing number of interventional treatment strategies have been developed and delivered by trained and certified personnel. They make use of the behavioral and learning trends ASD subjects tend to have. For example, many children with ASD focus and engage when they come in contact with physical objects that can move and be touched [44]. In recent years, robots have been used as special physical agents to interact with children, adults, and older people living with social, physical, and cognitive disabilities [45]. For example, the Canadian Medical Association (CMA), (2018) reported that around one to two percent of people are affected by ASD in Canada and the majority of these persons and/or their families do not have the resources to access adequate intervention treatment resources. This shortage of affordable services greatly affects individuals who not only suffer from conditions that could have been mitigated but miss the opportunity to further develop socially and acquire certain skills which could lead to some form of employment. This constitutes an obvious failure to apply prevention, which results in significant public costs associated with the lifelong support of these individuals. Evidently, the use of technology can enable the implementation of large-scale intervention treatment, which is very important for ASD patients and financially beneficial to themselves, their families, and their community.

Coming back to intervention-based treatment, scientific evidence by Wong et al [47] substantiates that Evidence-Based Practice (EBP) interventions are effective for children with ASD. In 2014, the NPDC (National Professional Development Centre) on Autism Spectrum Disorder, formed in the USA, classified 27 ASD related evidence-based intervention strategies, listed in Table 2 as most effective EPBs for children with autism [48], [49]. Below is the list of the 27 EBPS.[2]

[2] Treatment practice based on these EBPs has been implemented in over 200 schools in 12 states across USA and has currently been introduced in several other countries including Australia, Sweden, Poland, and Saudi Arabia.

Antecedent Based Intervention (ABI)	Naturalistic Interventions (NI)	Self-Management (SM)
Cognitive Behavioral Intervention (CBI)	Parent-implemented Interventions (PII)	Social Narratives (SN)
Differential Reinforcement (DR)	Peer-mediated Instruction and Intervention (PMII)	Social Skills Training (SST)
Discrete Trial Training (DTT)	Picture Exchange Communication System (PECS)	Structured Play Groups (SPG)
Exercise (ECE)	Pivotal Response Training (PRT)	Task Analysis (TA)
Extinction (EXT)	Prompting (PP)	Technology-aided Instruction and Intervention (TAII)
Functional Behavior Assessment (FBA)	Reinforcement (R+)	Time Delay (TD)
Functional Communication Training (FCT)	Response Interruption/Redirection (RIR)	Video Modelling (VM)
Modelling (MD)	Scripting (SC)	Visual Supports (VS)

Table 2.1: The 27 most effective Evidence Based related intervention strategies for supporting a child with ASD currently implemented across the USA and other countries [49].

In 2017, the Ontario Association for Behavior Analysis Inc. (ONTABA) [50] also reported and classified scenarios for which the evidence based practices can be used. It states that EBPs can be used based on expert clinical judgment, client values, and quality of intervention. It further mentions treatment and interventions can be classified as *promising*, *emerging* or *probably effective*. Many interventions fall into a category that is not established due to a lack of adequate evidence on their use and effectiveness. See Table 2.2 below for other terms used for classification [50].

Evidence Based Best Practice Proves Effective	Emerging Some (weaker) positive Evidence	Not Evidence Based	
		Insufficient Evidence to inform decision making	Best Practice Ineffective/Harmful
Well established	Emerging	Unestablished	Ineffective
Well validated	Evidence informed		Not recommended
Well supported treatment	Probably effective		
	Practice with some support		Non-evidence based
Use	Use with Caution	Do not use	Do not use

Table 2.2: The Classification of quality of effectiveness of EBPs treatment and interventions: promising, emerging or probably [50].

Technology-aided instruction and intervention is identified as one of the 27 EBP intervention strategies and practices. It is referred to as the use of technology, namely: "electronic equipment, device, computer application, virtual network etc. as the central feature in supporting children with ASD" [49]. The majority of autistic children have social behavior deficiencies. Intervention consists of subjecting them to numerous expensive sessions with therapists. Over the past several years, there have been promising results [20] suggesting that social robots might have a role to play in the treatment of children suffering from ASD, which could cut the cost associated with treatment considerably. Unfortunately, the cost of robots used for this purpose remains undeniably high for many lower income families.

This research, therefore, focuses on the provision of a low-cost "tool" for use in TAII based activities.

2.3 Technology assisted intervention strategies in autism spectrum disorder

During the last decade of the 20th century, we experienced a significant and consistent increase in the use of technology amongst the population, including children, adults, and scientists. Increased use of technology by children and the observed strong positive response of ASD children to the use of technology for entertainment and/or non-physical communication, generates the opportunity to use it in treatment activities, something that has been explored by numerous researchers and therapists [51], [52], [53]. According to a recent national survey of more than 5,400 children in Canada, 90% of children between age 12 and 17 had smartphones. 95% of them were online and had Internet access via some form of technology with 59% playing games, 52% reading social media posts, and 51% downloading and streaming movies, TV shows or music [54]. As children become more familiar and make more frequent use of technology, it becomes self-evident that exploring the use of technology in treatment is worthwhile. Children with ASD often require some external stimuli to begin, maintain, and terminate a certain behavior [28], which technology can provide. Autistic children find technology engaging and comfortable to interact with because they are visual learners and they can learn and possess strong technological skills [55]. Their interest in technology ranges from inanimate objects to computers, iPads, and mobiles phones. Evidence suggests that the integration of these technologies in intervention therapy for children with autism can assist their learning as well as the development of social and self-management skills. These technologies can be personalized to meet a specific need and interest of an autistic child and they can help to support earlier interventions for children with ASD [56].

Goldsmith and LeBlanc classified some digital technologies that have proven to be effective in intervening and instructing children with ASD, which includes Video-based intervention, Computer-based intervention, Virtual reality, and Robotics [28].

2.3.1 Video Based Intervention

The use of video technology is considered a useful tool among therapists and researcher, as it is readily available and requires little additional learning to operate. According to Sturmey, viewing a videotape showing correct behavior can have a positive impact on ASD children with respect to their social, language, and academic training [57]. In 2011, Junek [58] developed the “Mind reading interactive guide to emotions” CDs. It is an interactive guide that contains a collection of 412 emotions grouped into three main categories: emotions library, learning center, and games zone. Once installed, the video clips assist children with ASD to learn to understand their emotions in a fun way through games in which they can earn rewards. It is also a manager tool which parents, teachers, and professional can use to track the progress of a child and set limits. The CDs have proven to be the most adopted system [58] and this shows how the use of electronic screen media for video modelling, for example, can be useful [59]. It creates an opportunity to learn social skills, storytelling, basic communication skills, scheduling activities, and task completion as it utilizes a simple format of delivery, such as video tapes, to present information in a systematic manner that can gain and keep children’s attention [57]. Video based intervention can have better impact when combined with other treatment components such as role play and reinforcement [60].

2.3.2 Computer Based Intervention

When it comes down to their education, computer-based intervention has been proven to be beneficial to autistic children. When working with a computer, they become more motivated and display less behavioral problems [61]. Computing systems such as laptops, mobile phones, tablets, and various handheld devices are being used to teach a variety of skills such as emotions, behavior, reading, and communication. The idea is to focus on computer-based learning and identify exactly which areas improve the learning of autistic children and which do not. For example, is it the animation program which attracts their attention the most, and it could be because of the sound or features [62]. Researchers have explored several approaches to teach children with autism to develop skills in several areas, such as helping with problem solving, spelling and vocabulary, expressing and recognizing emotions, etc. [63], [64], [65]. Rehfeldt [66] developed an activity schedule using Microsoft PowerPoint to teach children with autism social skills, grammar, and vocabulary and the results suggest the outcome was positive [66] [67]. Evidence shows that the children became more attentive and showed more motivation when using a computer [68]. William Wright [69] showed that when children used computers, they seem to be engaged in a way that motivates and increases their learning patterns, compared to the traditional way of learning [69]. Madsen [53] used a computer application with an ASD subject to capture, track, and interpret their facial and head movements, and shared a video evidence with the subject to teach them how they can change their facial expressions to demonstrate their feelings and ideas [53]. A clinical trial, which saw ASD subjects exposed to 20 hours of training with the computer program "Let's Face it" [70] reported that the training can help to improve their facial recognition and processing skills [71]. Children with autism become more attentive and motivated when using computer devices with animation, sound, and voice functionalities [69]. The programming of computers provides researchers and clinicians with unlimited usage and control, which they use to test, observe, and keep records of the learning trials of children with autism who have similar behavioral deficits to compare them and come up with better treatment and diagnosis solutions. Computer-based intervention has proven to be effective for developing reading, vocabulary, language and listening skills [72]. It is worth mentioning that a large population of persons with ASD also exhibit attention deficit problems like those exhibited by persons diagnosed with ADHD. A study conducted by Shirmohammadi et al, saw the development and integration of a new measuring system based on the application of EEG (Electroencephalogram) machine learning classifier and a recorder in a serious game play activity. The system targeted attention-deficit hyperactivity disorder (ADHD) patients. It was the first of its kind to have been developed. The system is useful to detect, train, and strengthen the attention span of individuals experiencing ADHD. Results obtained from the EEG data showed 96% to 98% accuracy in detecting the correct attention state of healthy ADHD patients during gameplay. This shows a positive effect on the attention span of ADHD patients [73].

2.3.3 Augmented Reality

Augmented reality enables the fusion of real visuals and audio with computer generated information, images, and digital objects, and it does so in real time [74]. It also supports autonomous control of the environment in a three-dimensional, computer-generated form in a non-immersive way in real time and offers people the opportunity to behave in a virtual way and take on the results of their own behaviors. Researchers and therapists are exploring this technology to encourage learning with the introduction of distraction stimuli to create training materials that teach social play skills to a child with autism [75]. The use of this interactive technology was investigated extensively with non-autistic children and the results were promising [56]. It was used as a method of treatment for children with cerebral palsy to master the safe use of a wheelchair [76]. To assist children with social skills, Bhatt et al. [77] developed two augmented reality games. The games, which were Happy Minion and Emotion Game, monitored the level of engagement of the certain children with autism and encouraged them to try to recognize human emotional and facial expressions. The games also featured a web camera to record the user's facial expressions and had a motion-tracking device. An analysis of feedback collected after the study showed that augmented reality based games helped to increase and develop symbolic play and improve the social skills of children with autism [77]. Shirmohammadi et al. [78] developed a serious game which includes a Tangible User Interface (TUI) and a Graphical User Interface (GUI) to compare its effect on ASD subjects. The TUI was made up of physical Lego-like building blocks which were augmented with electronic modules. Results showed that TUIs stimulate social interaction and collaborative play in children with ASD compared to GUI based video games, and it was observed that children engaged in less isolated play and achieved improved performance overall [78]. Although augmented reality provides a very realistic and safe space for children with autism to learn social skills, as it attracts their attention, it presents a disadvantage in the form of cost, programming requirements, and the lack of accessibility by therapists and clinicians [56].

2.4 Capability Model and Key Components of a Robot

In 1942 Issac Asimov [79] introduced three rules knows as "The three laws of Robotics" These laws are intended as a safety feature to guide the design of any robot and they should not be bypassed [79]. The three laws of robotics are:

Law 1 – "A robot may not injure a human being or, through inaction, allow a human being to come to harm".

Law 2 – "A robot must obey orders given to it by human beings except where such orders would conflict with the first law".

Law 3 – "A robot must protect its own existence if such protection does not conflict with the first or second law".

The design and operation of robotic systems also require a host of other components and knowledge base to make them functional in any applied setting. It is important to consider the common hardware components used in robotics before carrying out any design and build for a robot [80] [81]. These key components include the following:

- Sensors
- Power electronics and actuators (muscles)
- Hardware/computer interfacing (controller)
- Computer programming

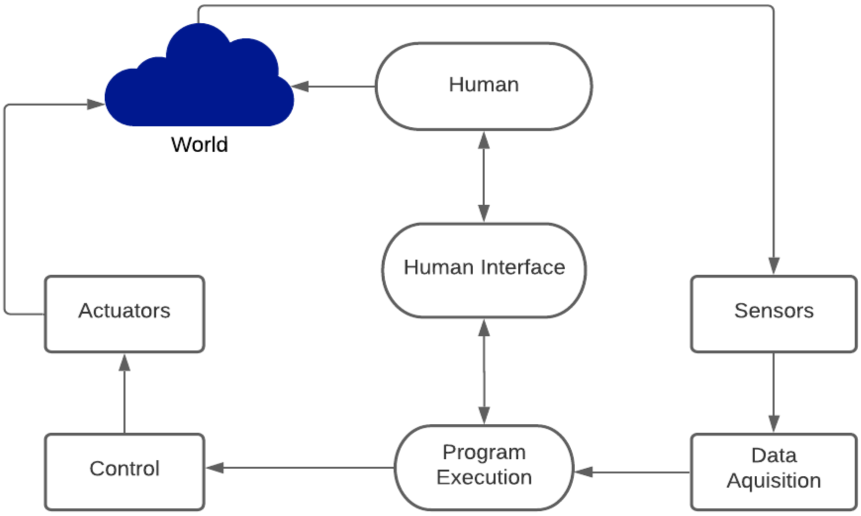


Figure 2.1: The block diagram design architecture of a typical robotic system [80] (Image re-created by Author).

The above components require a typical knowledge base in disciplines such as computer science, electrical and mechanical engineering, mathematics, physics, psychology, etc.

2.4.1 Sensor System

Robots often require information that is beyond the five human senses (sight, sound, touch, taste, and smell). Sensors help robots to detect, perceive, and share information about various things in its environment with the user or other interconnected modules. Examples of sensors include vision, light, and proximity [82].

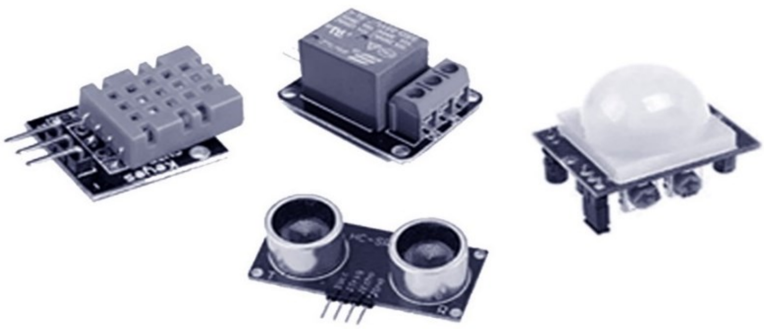


Figure 2.2: Examples of sensors: PIR motion, Ultrasonic, DHT11 and Relay sensors used in robotics design depending on functional and performance requirements [82] (Image re-created by Author).

The energy consumption of a sensor system can be calculated by

$$E_{sensor} = P_{sensor}\ x\ \Delta t \qquad (2.4)$$

$$E_{sensor} - electrical\ energy\ consumption\ and$$

$$P_{sensor} - electrical\ power\ of\ sensor\ system.$$

2.4.2 Motion/Animatronics System

Humans are very sensitive to the perceived motion of an object around them regardless of its appearance. Motion is an important aspect of interaction and expression, and the actuator, which allows a mechanical system to move, is a key component necessary to make a robot move [83]. These components are very critical for a robot; they make it possible for a robot to have physical interaction with its user. Many robotic actuators use a combination of several electro-mechanical devices, which includes continuous rotational motors and servos. These devices make possible to transfer adequate torque directly from a motor to the motion system of a robot for the robot to move [84].

The formula to calculate torque is given by

$$\tau = rF \sin\theta \qquad (2.4.1)$$

$$\tau = Torque, r = radius, F = force, \theta = Angle\ between\ torque\ and\ lever\ arm$$

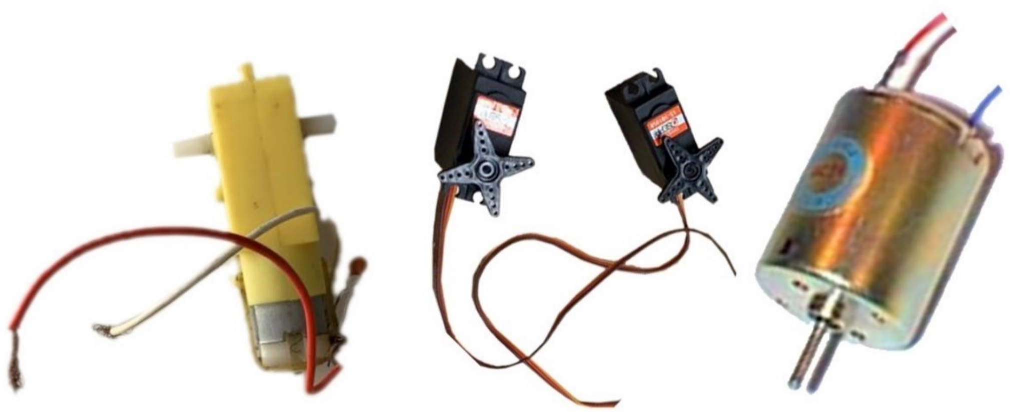


Figure 2.3: Examples of Actuators: DC and servo motor for use in applications to make a robot physically move or animate (Image created by Author).

2.4.3 The Controller System

The control interface system is the integration hardware unit that controls and coordinates other interconnected components of the robot. It is the brain of a robot and provides the essential sensory information and commands for actuators to perform tasks as well as control the robot [85]. It allows hardware units to interface through a digital controller with the outside world (sensors and actuators). The computing engines in the controller unit computes the control commands and the controller system can include both internal and external communication systems [86]. PC based microcontroller systems are the most widely used robotic controller systems for any application involving DC and servo motors. They can be programmed, powered, and connected to a computer for communication, and other components can interface with them easily, such as Arduino and RaspberryPi microcontroller boards [87] [88].

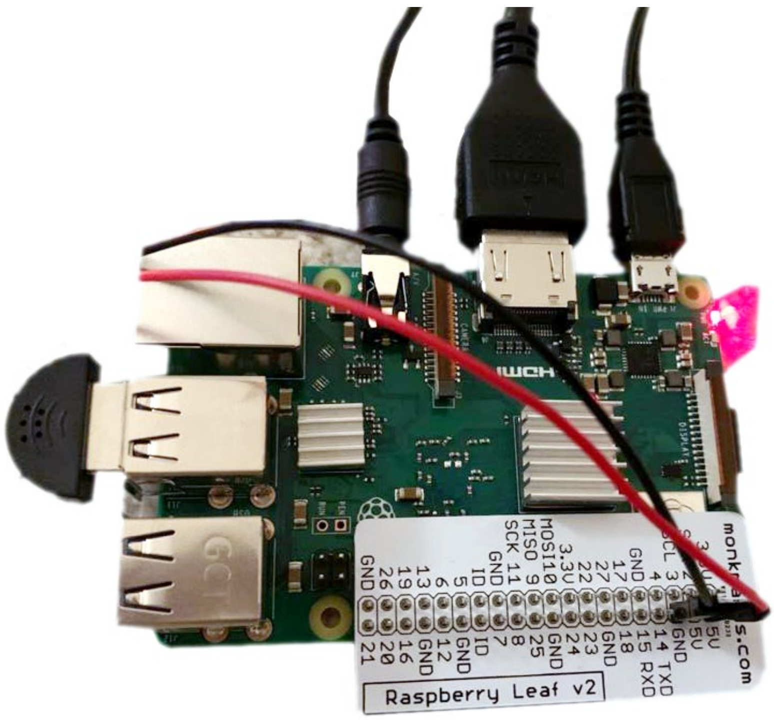


Figure 2.4: A RaspberryPi microcontroller development board with pin configuration for robotic applications (Image created by Author).

2.4.4 Power System

The power system is what provides electrical energy to an entire system of the robot. The power supply is a vital component to the operation of the interconnected electro-mechanical parts of a robot including the microcontroller. Batteries are the most common source of power supplies for most robotic applications [89]. They are classified as rechargeable and non rechargeable. Lithium-ion, Nickel metal hydride, and zinc batteries are some rechargeable batteries that offer increased energy [90] [91] [92]. The power requirements will determine if a robot will be a high or a low electrical voltage system and the sum of required power for all interconnected components should be lower than the voltage, which is the current capacity of the battery [93].

Power supplied by/to a system can be calculated by,

$$Power = Voltage\ (V) * Current\ (I) \qquad (2.4.2)$$

And the energy consumption of a robotic system is given by,

$$E_{elec} = P_{source}(t) \qquad (2.4.3)$$

$$where\ E_{elec}\ is\ energy\ consumption,$$

$$P_{source}\ is\ power\ from\ source\ and\ the\ interation\ is\ between\ the\ starting\ and$$

$$finishing\ time\ instances\ of\ the\ system's\ operation.$$

Figure 2.5: Examples of rechargeable battery power supply: Alkaline and Nickel Metal Hydride (NIMH) battery devices used for robotic design applications [93](Image created by Author).

2.5 The Robot's Appearance

The appearance of a robot, which can be humanoid, mascot-like, or animal-like, can play an important role in how children with ASD engage, learn, and bond with the robot if the objective of treatment is to promote simple interaction and social skills. Based on appearance, we divide the robots designed for ASD therapy into two categories:

a) Humanoid robots, which can also be referred to as anthropomorphic robots; and

b) Animal-like robots, also referred to as zoomorphic robots.

2.5.1 Humanoid Robots

Humanoid robots are robots designed to look like humans. They have human-like features such as eyes, mouth, arms, and legs. They are useful to have for children with autism to engage in play activities, socialize, and participate in imitation and emotional games and related activities. No guideline or specification exists for the design of a humanoid robot in terms of physical appearance. Robins et al. [36] [36], performed a study with a group of autistic children using ROBOTA to verify if the robot's appearance affected how the children engaged with it. The study saw ROBOTA dressed as a doll as opposed to a man dressed in a business costume, acting like a robot. The results obtained showed that the children were actively interested and engaged with ROBOTA when it was in its less human-like form. It was concluded that robots designed to interact with autistic children should not be too complex, containing exact human-like resemblance, but should rather maintain some generic humanoid forms and features. This guideline was used to design KASPAR [36]. During a study at the National Institute of Information and Technology in Japan, researches also observed some interesting traits in children with autism when they were subject to play with the robot INFANOID [94]. It was observed that the children paid more attention to the mechanical moving parts of the robot than the robot's ability to interact or communicate. This confirms the belief that children with autism love to engage with simple moving objects [94]. KEEPON is another example of a robot with humanoid features [95]. The robot's design contains features such as eyes, nose, an attractive costume, flexible body parts, and its ability to play music. The robot uses these features to capture the attention of the child, communicate interest, and encourage the child to engage in social and play activities [96].

2.5.2 Animal-like Robots

Many animals such as dogs, cats, rabbits, and parrots have proven to have therapeutic effects on humans in terms of emotional, mental and, psychological wellbeing. These pets were studied by researchers and made into robots, for example the "joy for all cat" and puppy robots by Hasbro [97]. These robots have gradually become more advanced and popular among people living with ASD. They were developed as therapeutic tools for children as well as elderly individuals living in elderly care facilities. It is known that animated pet-like robots can show comparable traits of attachment just like real animals. They have the potential to show suitable interaction, engagement, and communication through activities such as speaking, moving their body, following their owners around, and making noise around them to indicate their presence. To researchers this meant that robots can cling to and develop meaningful relationships on their own [98]. Activities and research undertaken by Boucher et al. [99] indicated that animals such as teddy bears are also good agents for testing pretend play activities with autistic children. They are good for testing a child's ability to develop social skills during play activities [99]. An end of year review by John Akins, a classroom teacher for children with autism, showed that one of his students, Karen, developed a significant attachment towards her teddy bear named "Arthur". She used the toy bear to calm herself down without being encouraged to do so and this decreased her tantrums. It was seen that she developed a great relationship with Arthur and Karen took the teddy bear to school, fed it, dressed it, and sang to it, and it helped her stay calm and engaged in social groups for 15 minutes or longer [100].

Table 2.3 provides a list of other robots developed to support intervention for children with autism and their brief description and what skills they were designed to target [101].

Robots	Description	Skills Targeted
TEO4 [102]  Image under CC by 4.0 (https://creativecommons.org/licenses/by/4.0/)	This robot is 80 cm tall, and it can move and speak; it has camera, touch, and distance sensor. Its face is magnetically interchangeable with autonomous reactions and pilot operation.	It is used in game activities for children with autism as a companion robot. It also reacts to touch.
QT Robot [103]  Image under CC BY-SA 4.0 <https://creativecommons.org/licenses/by-sa/4.0>	Uses a screen as its face and has a built-in 3D camera, WIFI connectivity, and microphone to listen to conversations. Can freely move its upper body to exhibit gestures.	It can support and improve recognition of emotions, body language, and active engagement.

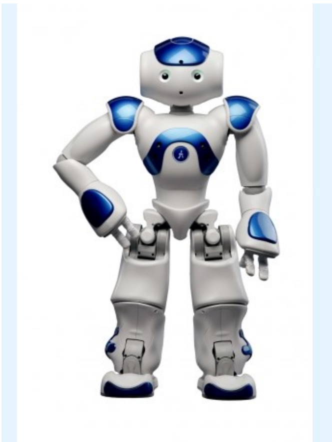
CARO [104]  Image under CC BY-SA 4.0 <https://creativecommons.org/licenses/by-sa/4.0>	This 93cm tall robot features a depth camera and touch and screen sensor with LEDs and RGB camera.	Caro helps children with ASD to engage in emotional play, mainly focusing on their expressions which is expressed with the eyes.
NAO [105]  Image under CC BY-SA 4.0 (https://creativecommons.org/licenses/by-sa/4.0)	This 50cm tall humanoid robot features WIFI, camera, microphone, speaker, and LEDs. It can move and allows for personalisation. It is suitable for use in clinics and educational environments.	It is used as tool for ASD intervention to improve attention, eye contact, pointing, and imitation. It can support with social interaction and the development of academic skills.

Table 2.3: Several other robots developed for ASD intervention [101].

2.6 Use of robotic technology for treatment of children with ASD

Although the application of robotics to support children with special needs like autism seems like a relatively new approach, it was first investigated 33 years ago by Yin and Moore in 1987 [106]. There have been many investigations into robots interacting with autistic children which have appeared in computer science documentations. The most notable researcher showed a great curiosity regarding the relationship between computing and behaviorism, and how that relationship can help to build tools that will improve the way children with autism are supported [107] [108]. Results of various studies [109], [110] show that while children with autism may have several other underlying issues, such as physiological issues or anxiety, these children show positive signs when engaging with robots. Using robots in intervention-based treatment can give researchers access to the social surroundings of children with autism and can help to make complex information easier for an autistic child to understand. For example, robots can be used in imitation games to inspire communication with a child with ASD [111].

According to reported research [112] there is proof that robots, in the form of a toy, are a useful tool in treatment. A beneficial use for the robot is to have it initiate the interaction with the child, "probing" for response, and for the robot to reply when the response is received, thus simulating interactive human-to-human behavior which is the foundation of social behavior [112]. For instance, in 1998 Dautenhahn Kerstin [34], started the project "AURORA", which stands for Autonomous Robotic platform as a Remedial tool for children with Autism. The Aurora project, conducted by a multidisciplinary team of researchers, was created to investigate how important the use of robotic tools could be to ASD intervention. Graham-Rowe, a reporter with Dautenhahn, mentioned specifically that the central aim of the Aurora project was to research just how a robot could serve as a "toy" and a teaching device as part of therapeutic interventions for children with autism [113]. Even though some people have a negative view of the mechanics of a robot, its imminent components and overwhelming evidence point to their usefulness as tools in treatment and support for children with ASD. Proper use of robots helps autistic children to connect with the social world of non-autistic people [61].

Figure 2.6: AURORA – The non-humanoid, truck-style robot platform used in the AURORA project, donated by Applied AI Systems, Inc in 1998 [114].

The first phase of the AURORA project released a truck-style toy robot. The designers believed that a non-humanoid form of robot would make integration and interaction easy. A few of their earliest models had temperature and bumper sensors, which enabled the robot to detect any object in proximity and avoid obstacles. Researchers found it useful when they used it in some interactive exercises, such as "tag and follow the leader" imitation and turn taking games, in which they allowed the children with autism to move around freely with the robot. The developers of the AURORA robot further improved the first design to include an "eye" to serve as a central point of focus. This feature was added to capture the attention of the children, sense their presence and movement around the robot as well as encourage them to make eye contact.

Further improvement saw the release of a more modern edition called 'ROBOTA'. It was an off the shelf humanoid robot, which combines several electronic devices such as computer processors, motors, and sensors to sense movements, and it acknowledged gestures of people or objects around it and reacted to them. The ROBOTA robot made it possible for children with autism to have visual interaction and participate in activities such as imitating and pretending. In order to measure the impact of the robot's use in actual autistic intervention, in 2003, Dautenham, carried out 3 phases of study with 18 children with autism to determine their reaction to the robot ROBOTA as opposed to an ordinary non-interactive toy [115]. Analysis of collected results concluded the following: (a) children with autism view robots as a safe interactive partner; (b) successful child-robot social interaction lasted over 10 minutes, which means the method assisted the child to maintain their focus for longer than 10 minutes; (c) children liked the interactive and reactive nature of the robot compared to toys with non-interactive features which only have a repetitive mode; (d) the children were actively engaged when the robot attracted their attention in the form of a look or other movements [51].

In 2014, Robins & Dautenhahn also developed the humanoid robot KASPAR (Kinesics and Synchronization in Personal Assistant Robotics), [34]. and its use is targeted to children with ASD. KASPAR's autonomous software controls its head, arm, hand, and includes touch sensors to detect objects; it also includes a microphone and speaker for interaction. It was designed for both educational and therapeutic purposes. Evidence suggests that children with autism engaged actively in play activities with KASPAR due to its spontaneous nature [34].

Figure 2.7: The humanoid robot KASPAR was designed with head and hands and includes touch sensors to detect objects around it; it also has microphone and speaker for communication [116] (Image under © Copyright 2020 IEEE - https://robots.ieee.org/robots/kaspar/).

Boccanfuso & O'Kane carried out an experiment with the robot CHARLIE [6]. CHARLIE, which stands for Child Centered Adaptive Robot for Learning in an Interactive Environment, was designed to behave like an actual human-being. Its hardware design includes 6 servos, which allows it to move its arms, and it also has a web camera, an LED generated light source to provide responses during interactive games, and it is covered in fur-like material so that it does not look threatening. It was used in turn-taking and imitation activities and the sensor in its face and hands helps to monitor users' movements during the play activity [117].

Figure 2.8: The Animanoid robot CHARLIE designed with eyes and mouth sensors to imitate movements in order keep children actively engaged [6] (Image under by © Medgadget, Inc - https://www.medgadget.com/2012/10/charlie-the-robot-is-helping-autistic-children-improve-communication-skills-video.html).

A therapist who used CHARLIE in a therapy session observed that the robot kept the children actively engaged by imitating the children's movements. CHARLIE is relatively cheap, approximately $200 USD, and accessible, making it a preferred choice of robot for most children with autism and for many therapists. It is imperative for parents, teachers, and therapists to bear in mind that, although robots can promote learning of social skills and behavior in children living with autism, they are not a replacement for a well-approved form of treatment. The robot should be used as part of a comprehensive and effective training program [117]. In Korea, on the other hand, a pet-like toy robot in the form of a dog was developed to support treatment for children with autism [118]. The robot acknowledges voice instructions, (e.g. sitting down and moving the tail) responds to stroking motions, barks, and can take photos. Although it is quite costly ($469 USD), it is very popular amongst children in

Korea. Another example is PLEO the dinosaur-like robot [119]. This robot can respond to touch, can be taught speech tips, and can understand the relationships developed between children with autism and robots. A study conducted by developers showed that the children lost interest in engaging with robots over time [119]. As a result, PLEO was further modified with the addition of a virtual technology that improved interaction, held the child's attention, and acted as a friendly companion [120].

2.7 Benefits of Robot Enhanced Therapy for ASD

As with many children, playing is an important aspect of a child's development, and this applies to autistic children as well. The main goal of robot enhanced therapy to date is the development of social and communication skills, which are very important for children with ASD. Robot research suggests that children with autism would rather play with a robot than play alone, and children with autism can also easily form relationships irrespective of factors such as appearance, age, and gender. Robots have the same specific and predictable characteristics such as tone of voice, body language, and visual appearance, thus not overwhelming the senses and processing system of the autistic child [121]. Because children with autism cannot concentrate for long periods of time, they might lose interest in socializing with a robot after a while. It is, therefore, imperative that children with autism should form some relationships to keep them engaged for a longer period of time [122].

A study was conducted by Sudha Srinivasan and Anjana Bhat in 2013 on children with autism between 4 and 6 years old; the study included non-ASD (control) subjects and a therapist using a 7-inch humanoid robot called ISOBOT [123]. The results showed that autistic children gave their full attention to the robot, maintained continuous interaction, and paid less attention to their therapist. Also, as the training and exercise during child-robot interaction went on for longer periods, results showed that the children with ASD got bored, paid less attention to the robot, and they began to look elsewhere compared to their non ASD peers. It was suggested that having a robot with more features and functionalities could help to alleviate this problem. However, attention and guidance from parents, caregivers, or therapists is also requires to initiate meaningful conversations between a child with autism and a robot [124]. A study conducted by Kim E. et. Al. in 2013 used a dinosaur robot, a human subject, and a computer game. Results showed that autistic children interacted more with the robot that was acting as a social partner and the therapist than with the human and computer game [125]. Additionally, in 2020, Prof. Cailin Hudson and Prof. Lundy Lewis conducted a 3-step research experiment using PARO, JIBO, Echo Dot speaker, and Cat and Puppy robots with ASD subjects aged 3 to 12 years-old at CHEO (Children Hospital in Eastern Ontario) in Ottawa, Canada. The children received therapy for up to 12.5 hrs per week and the purpose of the research was to determine the following: a) "what kind of robot are children with ASD attracted to", and b) "which ASD child profile(s) likes what social robot".

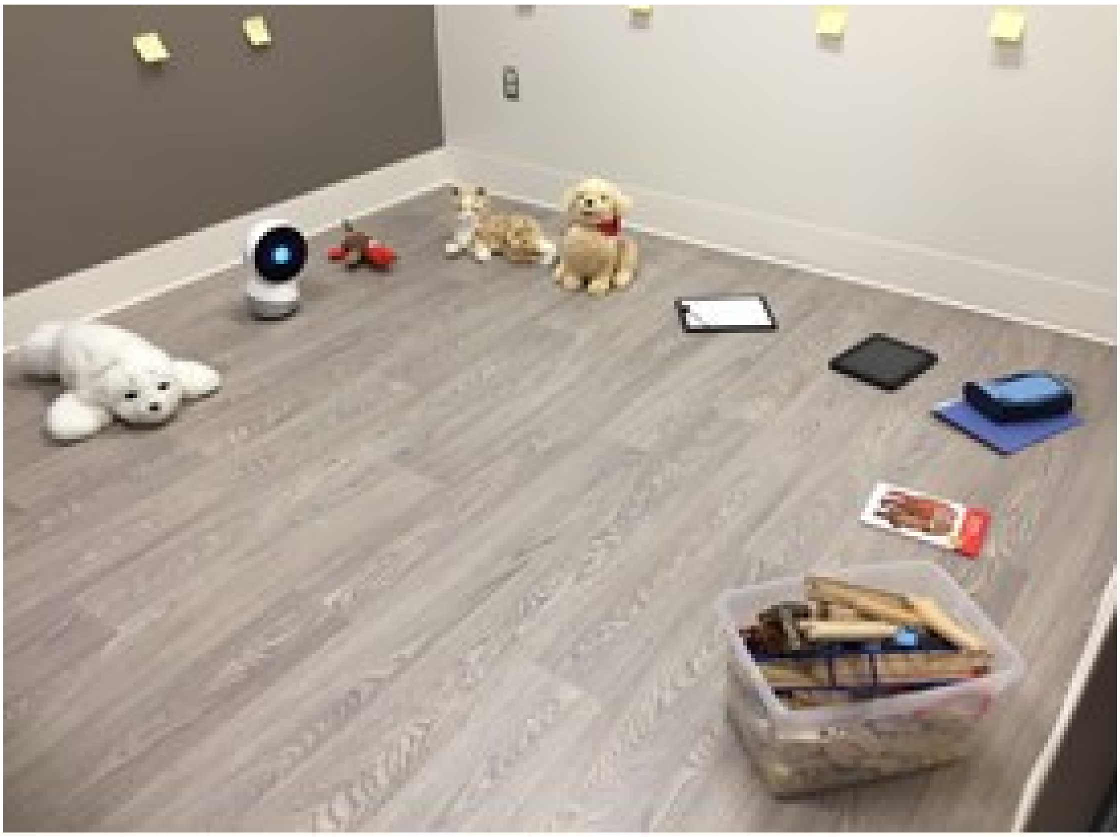


Figure 2.9: Experimental setup by Prof. Lundy Lewis with five commercial robots and reinforcers as part of therapeutic instruction for children with ASD [126] (copyright permission obtained).

Each of the five robots is autonomous and responds to sound and touch, except the Echo Dot speaker, and they were all declared safe to work with. Prof. Cailin Hudson and Prof. Lundy Lewis carried out a learning session three times with 9 subjects to determine how children with autism would engage with the different types of robots and if the children would prefer any one robot over the others. The results showed that four of the children were highly engaged with the robots while the other four were less interested. No one robot was chosen asa favorite over the others, but Echo Dot speaker was the least liked. This indicated that robots could act as part of reinforcement in intervention therapy that targets social skills acquisition for ASD children. In conclusion, research and evidence proves that these robots can play a significant role in intervention therapy of children with ASD [126].

2.8 Cost Analysis

The following table compares the cost of several commercially available social interactive robots discussed earlier.

Commercially available social robot	**Cost (USD $)**	**Commercially unavailable social robot (research)**
PARO	$6400	Robota
JIBO	$899	Lexa-Bear
Lynx	$800	GIPY
KASPAR	$2000	Probo
Joy for all collections	$100	
NAO	$7990	
PLEO	$469	
CHARLIE	$200	

Table 2.4: List of social robots and cost of commercially available ones.

As we can see from the above table, robot assisted therapy proves to be an innovative alternative in the diagnosis, treatment, and support for children with autism, but the cost of purchasing them creates a barrier for many families, especially the low-income ones. Therefore, this experimental research work, upon completion, will contribute greatly to broaden the scope of robot-assisted intervention therapy offered to autistic children. It will expand the offerings of intervention at an earlier age, which is when it is also more effective.

In conclusion, children with autism performed well when they had a robot as a tutor or a partner. The therapeutic needs of the child will determine how a robot is designed and how the robot will behave. The robots must be able to exhibit, perceive, and understand certain human behaviors, because what works for one child might not work for another.

2.9 Related Work

Robot assisted therapy proves to be a less expensive alternative, which can become an affordable solution for low-income families. It can enable them to provide the needed care and support to their ASD children while still being able to afford a satisfactory quality of life for their families. Recent advances in technology have enabled the development of several social companion robots that could assist children with ASD to learn, play, and develop social skills. Some of those social companion robots have been described in the following sections.

2.9.1 PARO

PARO is a social interaction and therapy robot designed to provide pet therapy for older people with dementia. It looks like a baby harp seal and is covered in soft synthetic fur. It supports the delivery of animal based therapy [127] to autistic children in a controlled environment and under the supervision of qualified therapists. Paro supports interaction between patients and caregivers. The expectation is that by using it, children with ASD will reduce their stress levels and negative emotions, making it easier for them to engage socially [128]. PARO provides patients with an experience that simulates the sense of touching a real animal [129].

Figure 2.10: PARO – A Therapeutic Animanoid robot which can be used for patients with autism to provide an experience that simulates the sense of touching a real animal [128] (Image under CC BY-SA 4.0 https://creativecommons.org/licenses/by-sa/4.0).

PARO has seen 8 revisions since its appearance in 2003 and has been used in Japan and Europe. It features five kinds of sensors: tactile, light, temperature, and the positions of people in its surroundings. PARO replicates the noise of a baby harp seal, which responds to the user's preferred behavior as if it were an actual human being by nudging its head and legs with sound output [130]. The PARO robot is available for approximately $6,400 USD.

2.9.2 JIBO

JIBO is an artificial intelligence powered robot. Its design features only two joints (neck and waist) with no arms or legs. It is equipped with facial recognition and touch screen technology. The robot can look concerned by turning its head towards the user and exhibiting a lot of emotion in its rotund body [21].

Figure 2.11: JIBO – A Social home robot with a 360 degree rotational body, intelligent voice commands and communication, and touch and facial recognition, which helps to create a genuine connection with its users. [21].(Image CC under https://creativecommons.org/publicdomain/mark/1.0/)

JIBO uses an intelligent voice assistant and advanced facial recognition technology to perform a variety of tasks, such as answering questions, connecting and turning lights on and off as well as interacting with other smart home automation devices. It can educate and create a genuine and personalized connection with up to 16 different people seamlessly [129]. JIBO can be purchased at approximately $899 USD.

2.9.3 Lynx

The Lynx robot uses Amazon Alexa's intelligent voice assistant to listen and respond to voice commands and it teaches yoga. It operates through voice activation and could be used to help manage a smart home device or browse through the web while playing music or checking the weather and traffic updates. It features a touch button to activate its voice assistant and surveillance camera, which can act as a smart home security camera. It can detect motion using a passive infrared sensor (PIR) [131]. The price of the Lynx robot is approximately $800 USD.

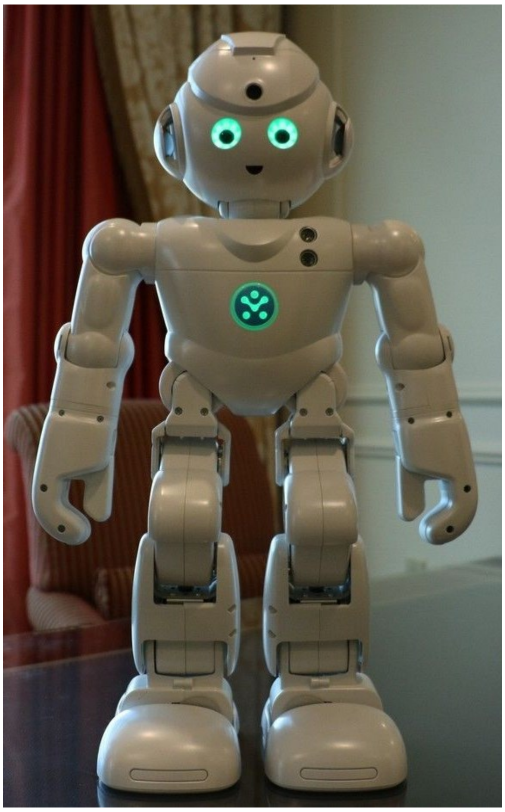


Figure 2.12: LYNX – A full Humanoid social robot equipped with Amazon Alexa for voice communication and interaction, with sensors and actuators which help to control physical movements [132].

2.9.4 Lexa-Bear

Lexa-Bear is a friendly and intelligent voice assistant teddy bear robot. It can hear and speak to the user. It can do a lot of fun and helpful things like checking the weather, checking the news, telling jokes, and telling bedtime stories. Lexa-Bear is designed to hold an Echo Dot plug into its circuitry to perform its operations. The robot animates its mouth and synchronizes the motion with its human-like voice in real time. It is highly adaptable for use with Bluetooth devices, mobile phones, and other voice controlled digital assistants like Apple Siri and Google Home. Lexa-Bear was set to sell for $149 USD. It is currently the subject of an intellectual property dispute and is currently unavailable [24].

Figure 2.13: Lexa-Bear – A teddy bear social robot designed with an built-in electrical circuit which connects to an Amazon Echo speaker for voice interaction with children [24].

2.9.5 Joy for All Cat and Puppy

The Joy for All Cat and Puppy robot collection developed by Hasbro [97], is a collection of animal-like robotic pets. They debuted in November 2015 and behave, sound, and feel like real animals such as cats and dogs. They were created as therapeutic companion animals for people with dementia and autism [34] and have been programmed with sound technology to mimic sounds around them. They also include sensors which allows for facial expressions and eye movements. They respond to being petted and hugged through vibration and purring and they do not sound mechanical. They also do not need to be fed like real animals.

Figure 2.14: Joy for All Cat and Dog by Hasbro – A collection of adorable animanoid social robots which children with autism view to be friendly, cute, and attractive [133].

They are very adorable and are perveived by many children and adutls living with austism to be interactive because of a variety in their movements. They are battery operared with a sleep and silent mode to save battery life. The Joy for All Cat robot can be purchased for $109.99 USD and the Joy for All Puppy robot sells for $129.99 USD [133].

Chapter 3: Proposed Design Prototype

This chapter describes and discusses our engineering approach to enhance the Lexa-Bear robot. It will also discuss the design and development of the hardware and software components of our robot's design. The proposed design will combine an Alexa voice service device, a software development kit (SDK), an off the shelf teddy bear, an onboard RaspberryPi microcontroller unit which will act as the central processing unit, a Bluetooth microphone and speaker, and other electronic components and software programs. The Alexa voice service allows speech input when the user uses the wake word "Alexa", while the output audio responses are provided by the robot. The Microcontroller unit interconnects and controls all hardware and software programs that implement the robot's functions. The design also includes a PIR (passive infrared) motion sensor that supports an innovative device state mechanism, which enables the robot to sense body heat energy or moving objects and reacts to them by animating parts of its body. The designed robotic architecture also uses a DC power supply unit which supports USB C and direct supply. This means that the robot can be powered directly from a wall socket or a USB battery power bank supply.

Table 3.1 shows cost associated with purchase of devices used for the design of the proposed robotic prototype:

Materials	Cost ($CAD)
RaspberryPi	100
Teddy Bear	89
Alexa Voice Service	Free
PIR sensor	10
Actuators	16
Bluetooth microphone	10
Speaker	10
Total	235

Table 3.1: Design cost breakdown of electrical components used in the design of our proposed prototype.

According to the table above, the RaspberryPi and teddy bear incur the most significant costs as they act as the body and central processing unit of our design prototype. The teddy bear was expensive because it came with build in sound, a moving mouth, is R-Rated, and produces 5 phrases (explicit language).

3.1 Robot Design Architecture

The design and implementation of the robot involves hardware components (e.g. teddy bear, actuators, RaspberryPi, motion sensor, USB microphone, and speaker) and software components (e.g. Amazon Alexa voice service, Pacat, Pigiopd, Pulse Audio, a set of Python scripts, etc.). Figure 3.1 displays the hardware and software architecture of the robot in a block diagram format.

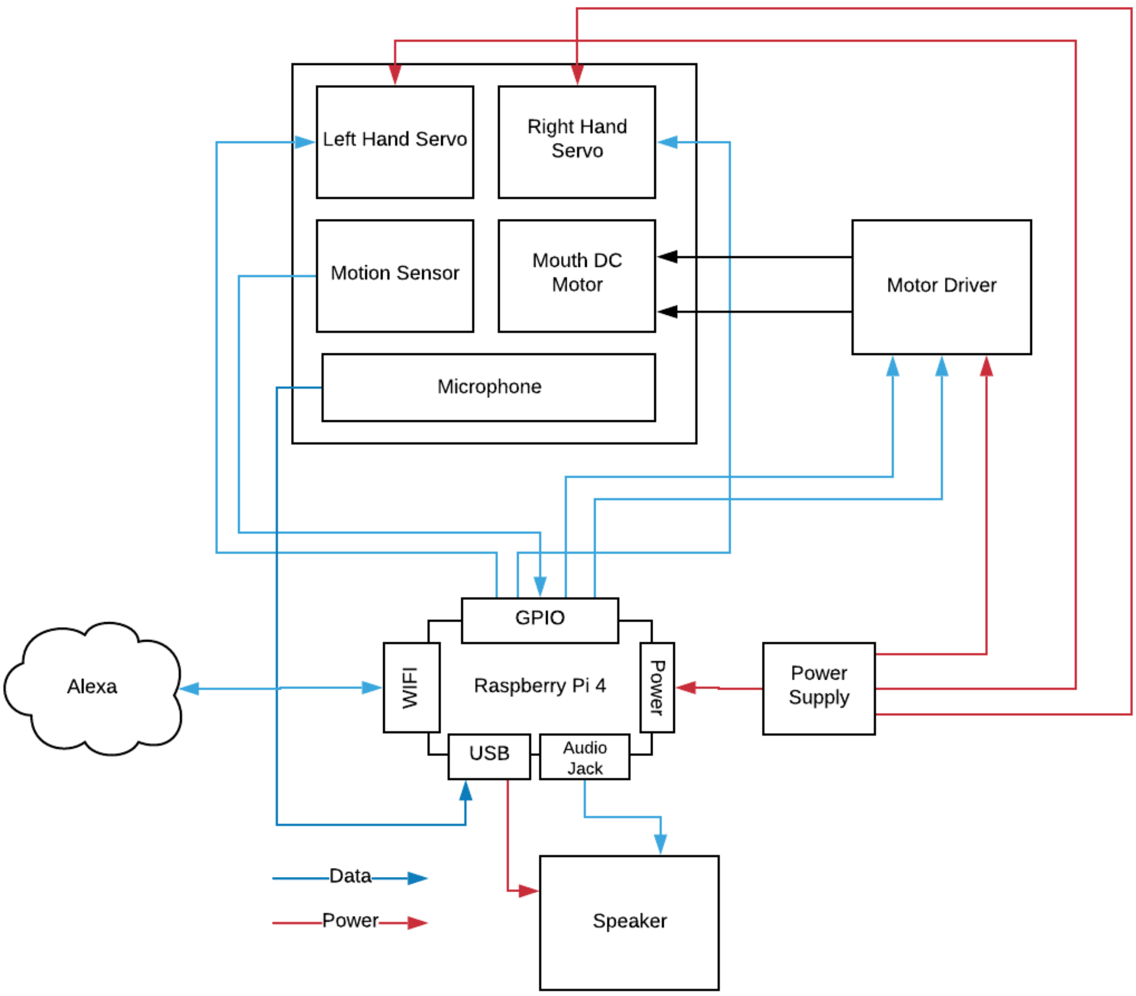


Figure 3.1: Hardware architecture of proposed design prototype with all interconnected components: RaspberryPi, speaker, microphone, actuators, etc. (Image created by Author).

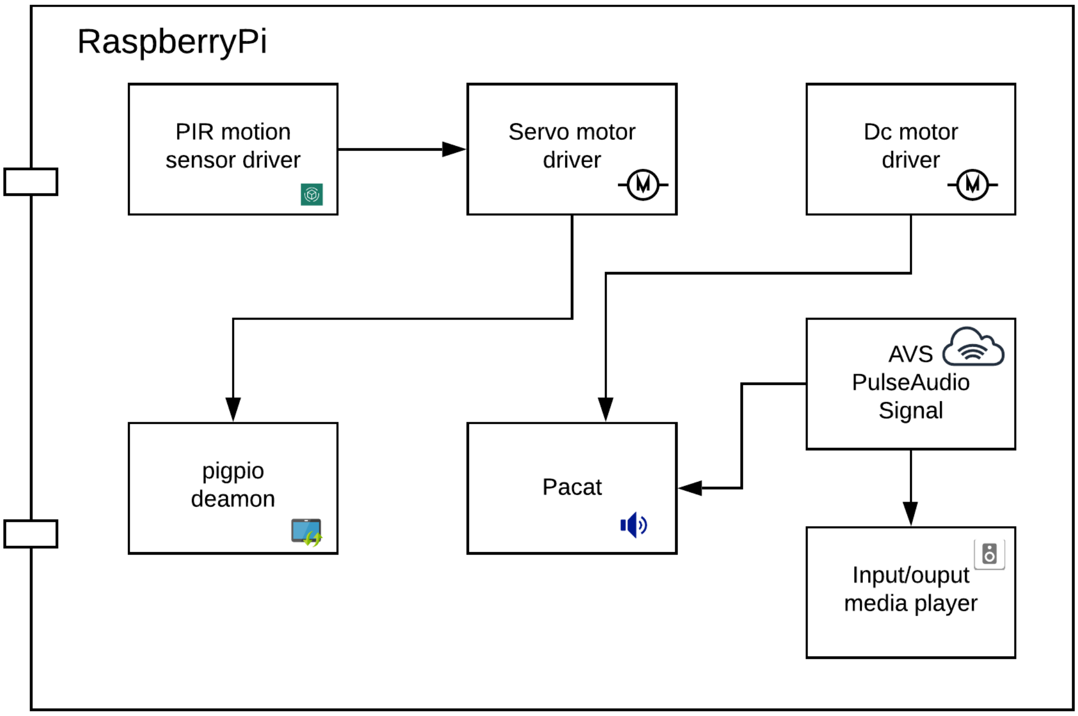


Figure 3.2: Software architecture and functional software packages: pacat, pigpio, and motor drivers compatible with and able to support the RaspberryPi microcontroller (Image created by Author).

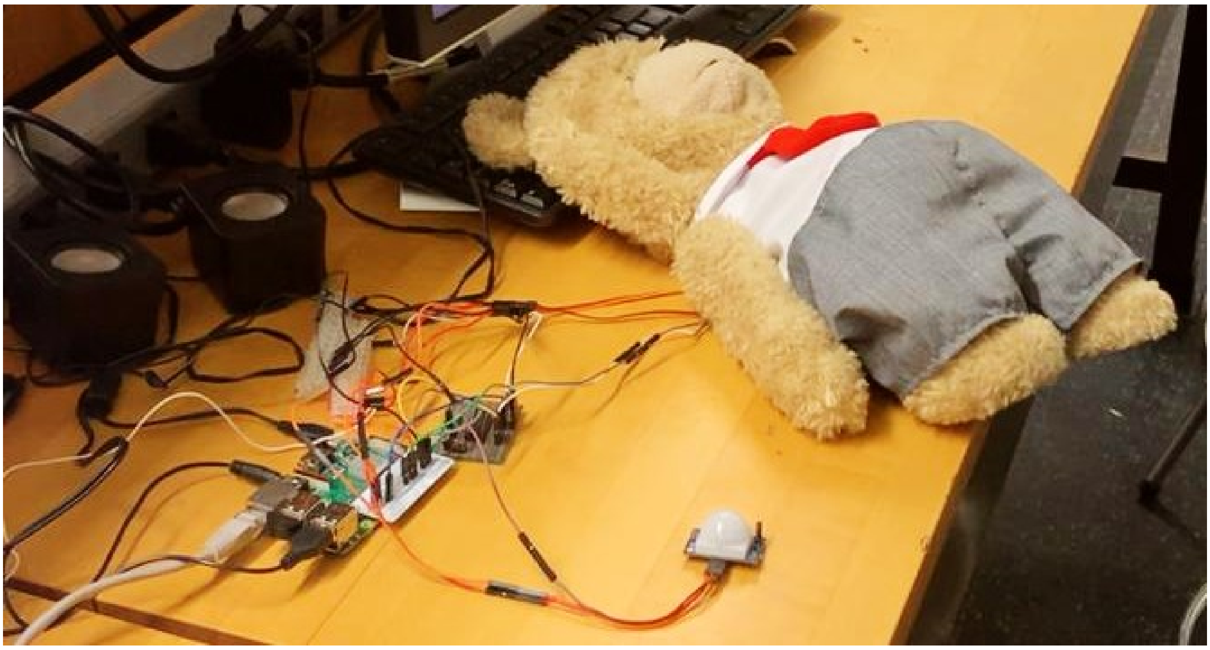


Figure 3.3: Laboratory setup and testing of robotic design prototype (Image created by Author).

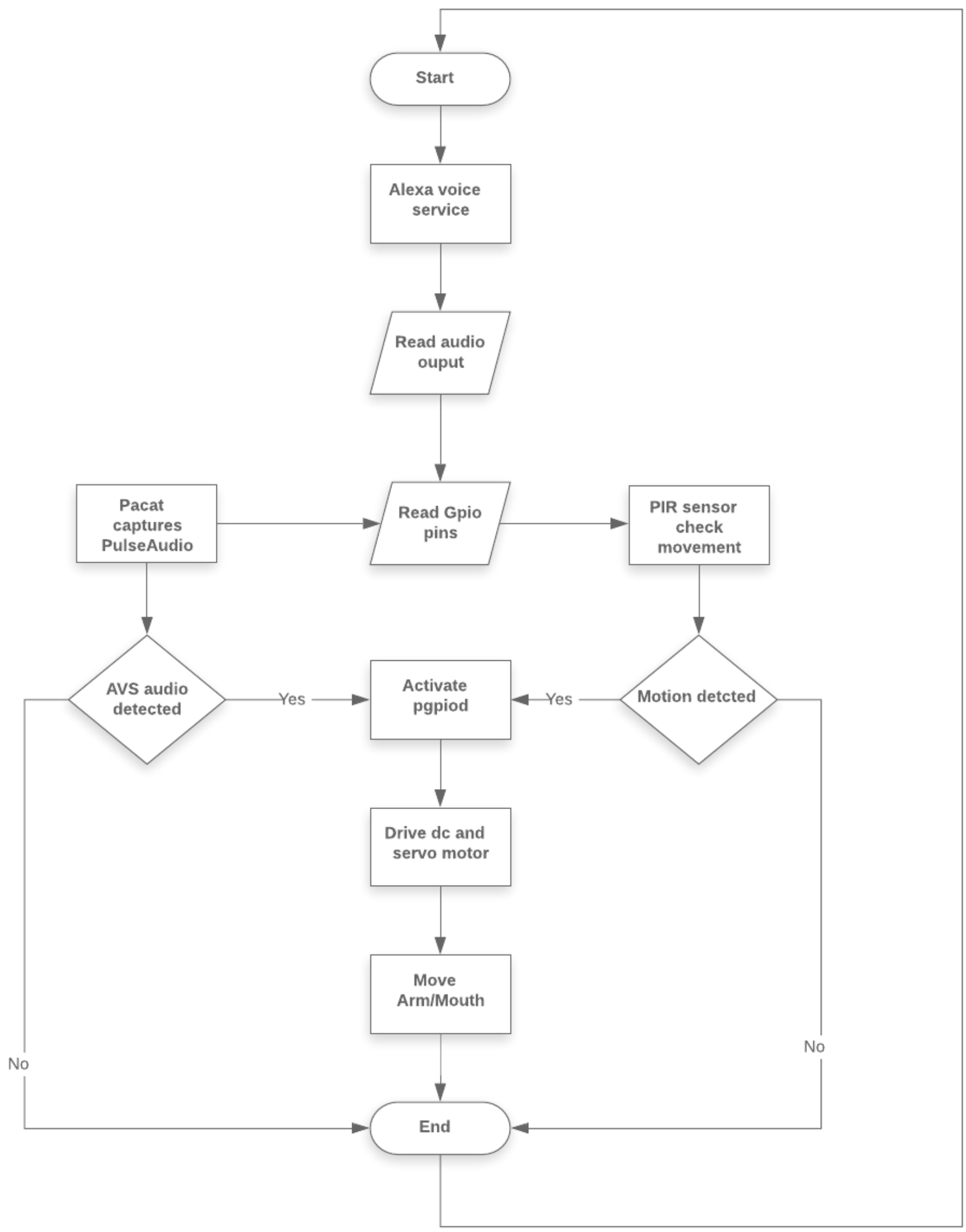


Figure 3.4: Flowchart of the proposed robotic system (Image created by Author).

3.1.1 Hardware Platform

The hardware platform of the robot comprises of a teddy bear [134], RaspberryPi microcontroller [135], DC [83] two servo motors [136], a PIR motion sensor [137], a microphone [83], and a speaker [83]. The teddy bear acts as the body or chassis of the robot and houses all the interconnected components.

Figure 3.5: Teddy bear used in the design of the robot prototype (Image created by Author).

Furthermore, the design includes actuators in the form of DC and servo motors combined with a L293d H-bridge motor driver that physically animates the robot. The servo motors are mounted on a 3D printed arm lever – manufactured locally by the author of this manuscript –

with a beam attached. This provides motion to the arm and mouth of the robot during a conversation.

Figure 3.6: Robotic Actuators: DC and servo motors with L239D motor driver used in the robot's design to make it physically animate (Image created by Author).

The PIR sensor detects motion within its field of view by identifying changes occurring in the background heat signature, thus detecting the presence of humans or animals that walk within the sensor's field of view. When there is no movement or motion around the sensor, there is no output of electric signal.

Table 3.2 indicates key configurations of the PIR motion sensor.

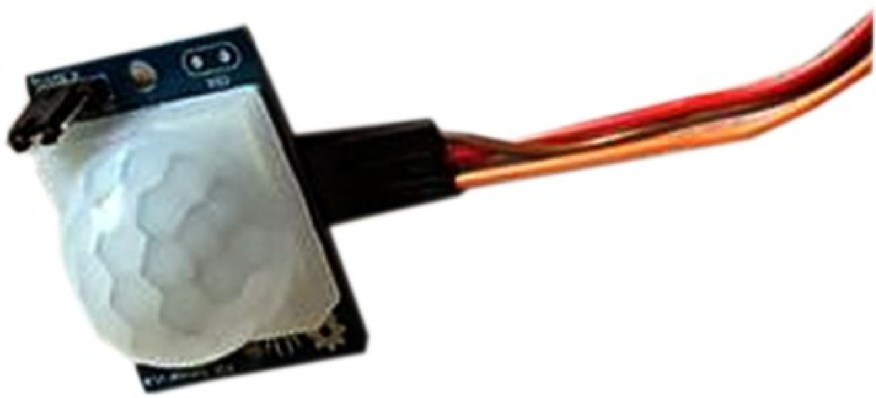


Figure 3.7: Robotic Actuators: A PIR motion sensor used in the robot's design to achieve device state and attention model (Image created by Author).

Component	Specifications
Power	1.5V DC
Sensor	Passive infrared
Standby state duration	1 min
Environmental setting	Indoor and outdoor
Temperature	-18^o C to 55^o C

Table 3.2: The PIR motion sensor practical device configurations [137].

These peripheral devices such as microphone, speaker, connecting wires, and USB cable support the interconnection of hardware, power supply, and data communication within the robot. The Bluetooth microphone is used to communicate with the Alexa voice service, while the speaker enables speech and sound output responses. The microphone and speaker connect to the on-board USB slots on the RaspberryPi.

Figure 3.8: Peripheral devices: USB power cable, microphone and speaker used for power supply connection and voice communication with the prototype (Image created by Author).

The process involved in successfully achieving the proposed design concept will be discussed in detail in the following chapters.

3.1.2 Software Platform

The software platform of the robot comprises of an Amazon Alexa voice service device SDK for voice interaction [25], Pulse Audio [138], Pacat [139], Pigpiod [140], and a set of Python scripts developed by the author of this manuscript specifically for this research work.

3.1.2.1 Pulse Audio

This is a powerful network-based sound server for Linux operating system desktop environment. It can be used to send/receive audio channels between a software application and a hardware device. The sound server allows for users to carry out advanced operations on audio sound data as it passes through an application and a hardware device to best suit its needs [141]. With Pulse Audio sound server, it becomes easy to transfer audio streams to a different machine, change the sample format or channel count, and mix sounds from multiple sources into one [138]. The rerouting of the audio stream is accomplished using modules such as '*pavucontrol*' or '*pacat*'[141]. Currently, Pulse Audio is present and running by default in most Linux desktop distribution systems, such as RaspberryPi, which is why no installation is required. Playback/recording devices, audio sinks and sources, and clients connect to Pulse Audio. Clients such as Amazon connect to the Pulse Audio sound server. This allows the Alexa voice service application to communicate with the hardware device, which includes running it over a network. The Alexa voice service device SDK uses Pulse Audio to record audio from the microphone, play music, and use Alexa text to speech [142].

3.1.2.2 Pacat

Pacat is a simple command line tool for recording and playing back raw or encoded audio files on a Pulse Audio server in Linux operating system's desktop environment. It supports audio formats such as Pulse Audio [142] and ALSA (Advanced Linux Sound Architecture) [143]. The following Pacat extension commands 'parec' or 'pamon' can be used to play and record raw audio data at the same time [139].

3.1.2.3 Pigpio Daemon

Pigpio daemon, also referred to as pigpiod, is a C and Python utility software library that can be used to manipulate and control the general-purpose Input/Output (GPIO) pins of the RaspberryPi, PWM (pulse width modulation), and servo motor. It launches the pigpio library as a daemon so that multiple programs can run continuously and remotely over a network. Running the Pigpio daemon[3] requires sudo privileges from the raspberry graphical user interface (GUI). It runs in the background and accepts commands from interfaces on the RaspberryPi [144].

The relevance of Pulse Audio, Pacat, and Pigpiod to this research work will be discussed in a later chapter.

[3] To install the pigpio deamon use the command – pip install pgpio
To run the daemon use – sudo pigpiod.
To stop the pgpio daemon use – sudo killall pgpiod.

3.2 Autonomous Microcontroller based Central Processing Unit

The RaspberryPi 3 B+ model was used in this research work as the central processing unit of the robot. It uses the Linux operating system (OS) and runs all the computational programs and processes required by the robot. The RaspberryPi was responsible for the handling and connectivity of hardware devices and software programs. It was selected because it offers faster processing speed, memory, multimedia, and WIFI network connectivity compared to other microcontrollers like Arduino [135]. It runs on a Raspbian NOOBS OS [145]. This is the compatible Raspbian OS recommended for the use and application of the Amazon Alexa voice service SDK [135]. The installation process of the Raspbian NOOBS OS on the RaspberryPi can be found in Appendix E.

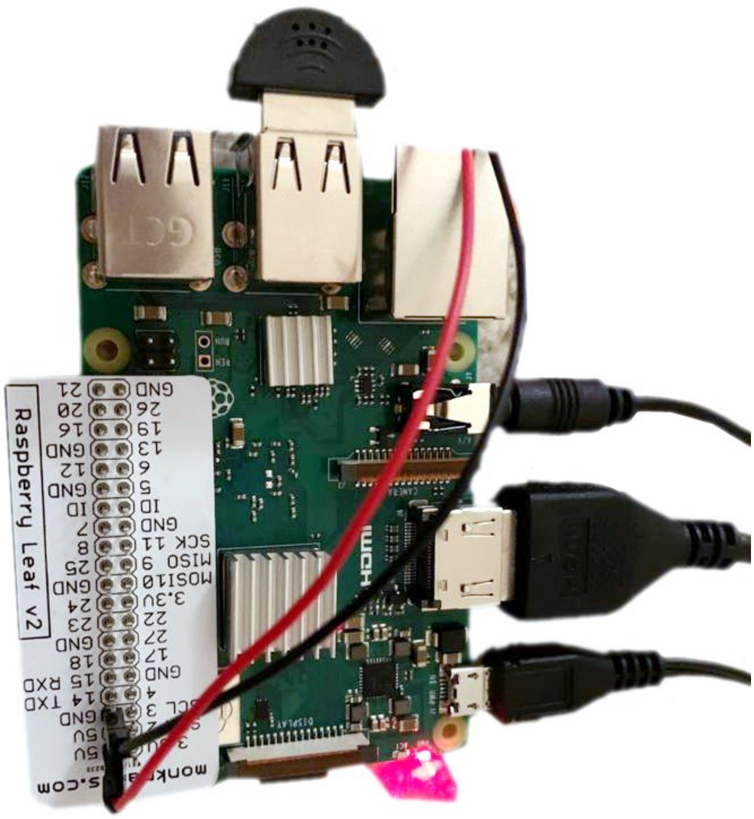


Figure 3.9: The RaspberryPi 3 B+ Model microcontroller board used as the CPU of our robot (Image created by Author).

Components	Description
SoC	BCM2837
CPU	Quad cortex A53 @1.2GHz 64-bit Processor
RAM	1GB
Storage Memory	Micro SD (32GB)
USB 2.0 ports	4
GIPO pins	40
Networking	Ethernet (10/100 Mbps) and Wireless 802.11n, Bluetooth 4.0
Video Output	HDMI composite
Audio Output	HDMI and Headphone Jack
Operating System	NOOBS
Operating current, voltage	5V, 2A

Table 3.3: Raspberry Pi 3 B+ design specifications for experimental applications and pin configuration [135].

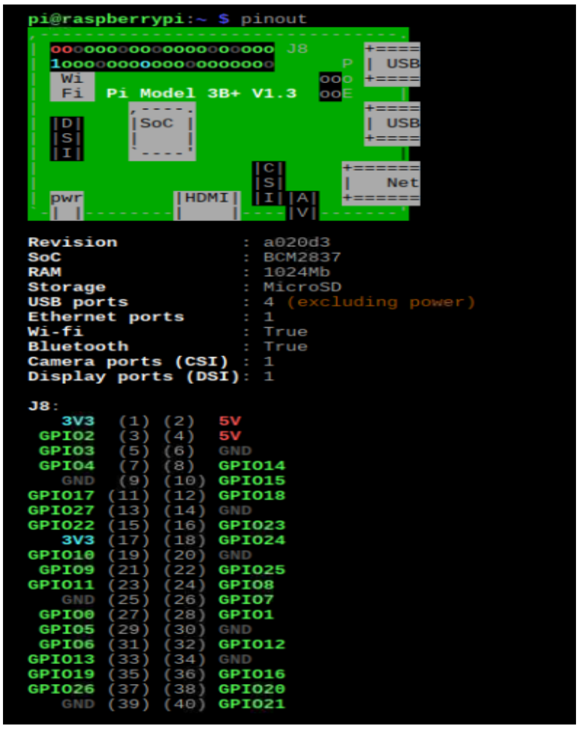


Figure 3.10: Raspberry Pi GPIO pins layout (Image created by Author).

3.3 Voice Interaction Algorithm

3.3.1 Amazon Alexa Voice Service Device SDK

The Alexa voice service device SDK (software development kit) is a set of C++ software libraries and APIs from Amazon that allows developers to provide cloud-based, Alexa voice-enabled functionality to any commercial device and product with a microphone and speaker to capture interaction and respond to voice requests. It was released in 2017 and is free to use and it is available at [146]. Its features include voice interaction, music playback, alarm notification, and managing network connectivity. A device interacts with an Alexa voice service in general in the form of events (messages that goes from the device to the AVS) and directives (instructions from the cloud that help the device to respond). For example, when a user asks Alexa something, the device captures the audio signal in the form of events to the Alexa voice service cloud. The Alexa service then issues a directive back to the device to do something. The diagram below illustrates the components and flow of voice interaction between a device and the Alexa voice service device SDK.

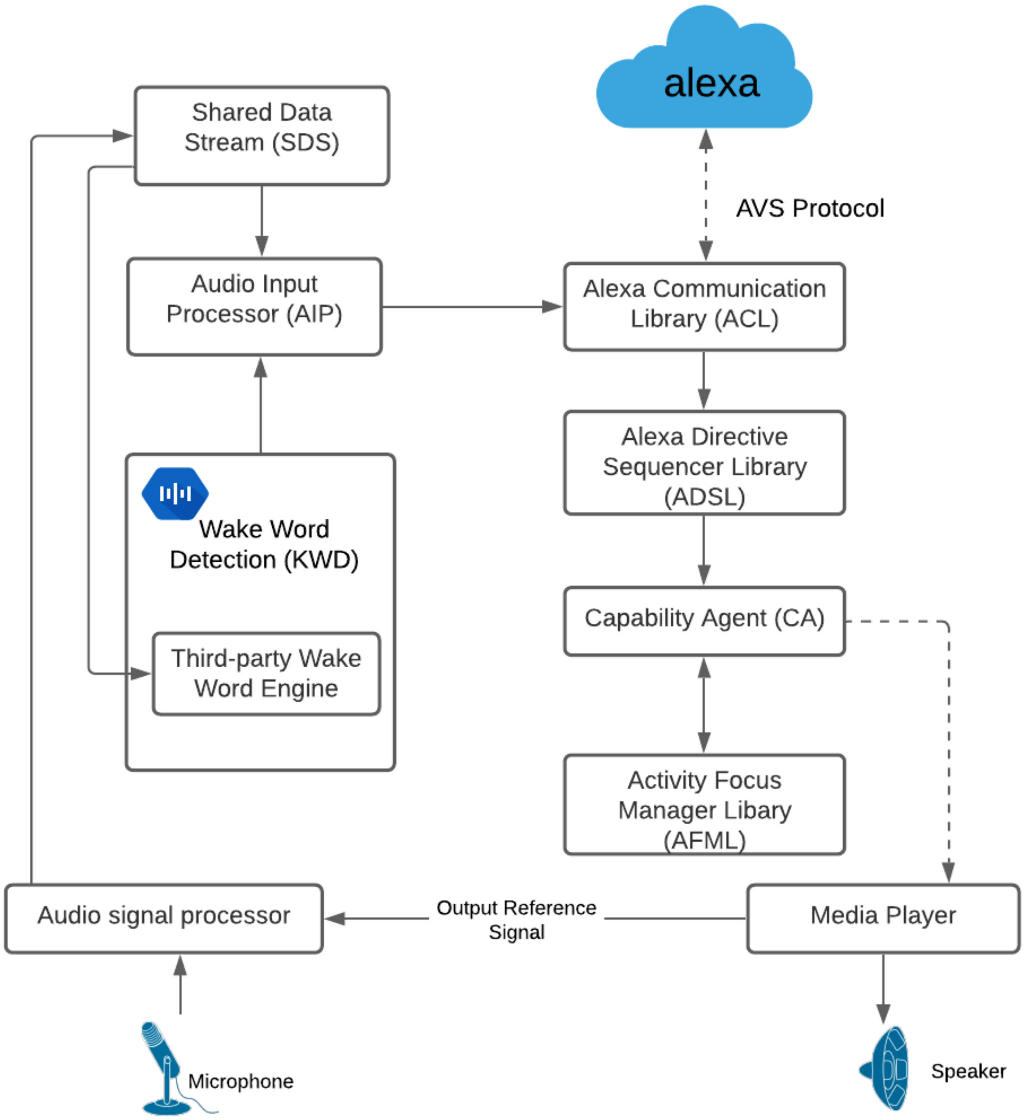


Figure 3.11: The Amazon Alexa voice service device SDK architecture [147] (Image re-created by Author).

3.3.1.1 Audio Signal Processor (ASP)

The Audio Signal Processor (ASP) is a software component that runs on a dedicated digital signal processor and “cleans up” the voice input audio signal received from the user via a microphone, creating a single, easy to process audio stream. The cleaning up of the audio signal includes echo cancellation, the elimination of background noise, a voice activity detector, etc. [148].

3.3.1.2 Shared Data Stream (SDS)

The Shared Data Stream (SDS) is an audio input buffer that stores the audio input signal captured from the microphone. The SDS distributes the audio data to the different components of the Alexa voice service application and allows it to pass throughout the components without duplication. It constantly overwrites itself, thus reducing the amount of memory it uses while continuously capturing data [148].

3.3.1.3 Wake Word Engine (WWE)

The Wake Word Engine (WWE) is a software component that is constantly monitoring the audio data delivered to SDS buffer in order to identify any trigger words that corresponds to the preconfigured wake word, which is generally known as “Alexa”. Once WWE detects the wake word “Alexa”, it notifies the audio input processor, which begins to read the audio. The Alexa voice service SDK includes a sensory wake word engine which handles the general wake word detection [148].

3.3.1.4 Audio Input Processor (AIP)

The Audio Input Processor (AIP) is a software component in the Alexa voice service device SDK that captures the audio input signal from the shared data stream buffer and sends it to the Alexa voice service for processing. It sends audio data only when the Alexa wake word is triggered from the wake word engine. The AIP contains the logic to process and switch between different audio input sources such as microphones, Tap-to-talk, and speech directive, and will continue to stream audio data until it times out or receives a stop directive [148].

3.3.1.5 Alexa Communications Library (ACL).

The Alexa communication Library (ACL) helps to handle and establish a secure network connection between an Alexa product and the cloud to send and receive messages. It also manages the network connection; for example, if a device disconnects, it automatically attempts to reconnect it. Once the message is sent to the cloud, the Alexa in the cloud processes the message and sends it back to the ACL as a directive. ACL takes the directive, instructs the device or product to act depending on the message specification detail, and then sends the directive to the Alexa Directive Sequencer Library (ADSL) [148].

3.3.1.6 Alexa Directive Sequencer Library (ADSL).

The Alexa Directive Sequencer Library (ADSL) handles and manages incoming directives and schedules their order of execution, including reordering or cancellation, and routes them to Capability Agents for handling [148].

3.3.1.7 Capability Agents (CA)

Capability Agents (CA) are responsible for handling and making sure the desired action on a device, such as interactions or events correspond directly to specific interface supported by the Alexa voice service. For example, when a user activates the wake word “Alexa” to play a song, the CA loads the song and plays it through the media player [148].

3.3.1.8 The Activity Focus Manager Library (AFML)

The Activity Focus Manager Library (AFML) handles the correct and consistent order of input and output directives across an Alexa device. It uses a concept called **Channel**[4] [149] to determine the order of priority[5] of audio input and output. Channel changes the activity level between foreground and background state. For example, if a user is listening to music and an alarm suddenly goes off, the alarm takes priority over the music by indicating to AFML that it wants the foreground channel to allow the alarm to ring. AFML pauses the music, sends it to the background channel, and permits the alarm to ring. When it is done, the music returns to the foreground channel [147].

---

[4] Note that only one activity can have the service of the foreground/background channel.

[5] When having more than one activity occurring at the same time, the following order of priority sequence is followed in order of highest to lowest: Dialog; Alerts; Contents.

3.3.1.9 Sample App

The Alexa voice service SDK features include a Sample App [25] that uses Pulse Audio [138] sound system configuration to capture audio from any input microphone. The sample App can be used to test voice interactions with the Alexa voice service using hardware audio devices, such as a microphone and speaker, before they are fully integrated [150].

Appendix A contains the process of installing the Amazon Alexa voice service device SDK program on RaspberryPi.

3.4 Animatronics and Motion

3.4.1 Animatronics

The animatronics of the robotic design in this research work is divided in two parts, namely: mouth and arm animatronics.

The design of the mouth animatronics framework of the robot came with the teddy bear by default so no additional work was required. The framework included a continuous rotation DC motor which was attached to the mouth of the teddy bear.

The arm animatronics of the robot, on the other hand, was designed using a 3D printed arm lever and two micro servo motors with a beam attached to its horn as shown in Figure 3.12.

Figure 3.12: A 3D-printed robotic animatronics lever arm and with servo motors attached to cause robot arm to physically animate (Image created by Author).

The arm lever and beam were modelled using Autodesk Tinker cad online 3D modelling software [151] and manufactured using the 3D printer available at the STEM (science, technology, engineering, and mathematics) Laboratory in the University of Ottawa.

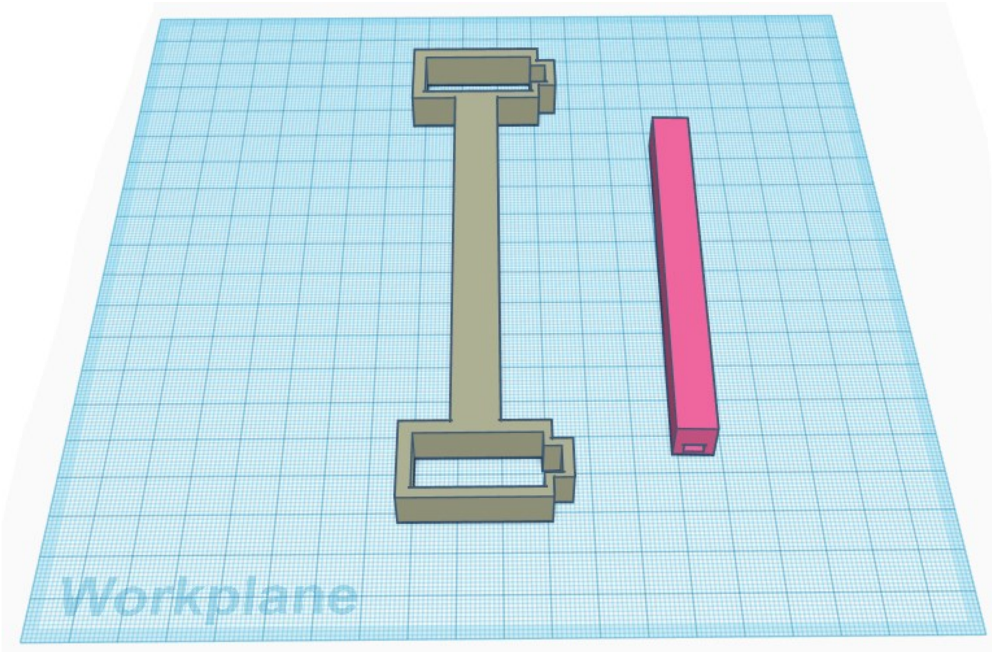


Figure 3.13: Modeling 3D-printed animatronic robotic arm lever and beam (Image created by Author).

The dimensions are:

Arm lever (mm)	Servo horn attachment (mm)
Length = 201	Length = 100
Width = 53	Width = 9
Height = 10	Height = 10

Table 3.4: Dimension for 3D animatronic robot arm lever and beam attachment.

The arm lever and beam were modelled with a hole in them. The hole acts as the protective holder and support for the servo motors. The servos were mounted on the right and left side of the arm lever using a glue, which includes the beam that is connected to its horn. The complete piece was placed inside the teddy bear and connected to its right and left arm. This provided the animatronics framework required for the robot to animate its arm.

3.4.2 Motion

The robot is designed to physically animate two parts of its body: the mouth and the arms.

3.4.2.1 Mouth Motion

As mentioned in *Table 3.1*, the mouth animatronics system of the robot was designed using a continuous rotation DC motor. The DC motor uses two terminal wiring configurations coded in red and black as shown below. The red terminal connects to 5V DC power supply and the black terminal connects to the ground.

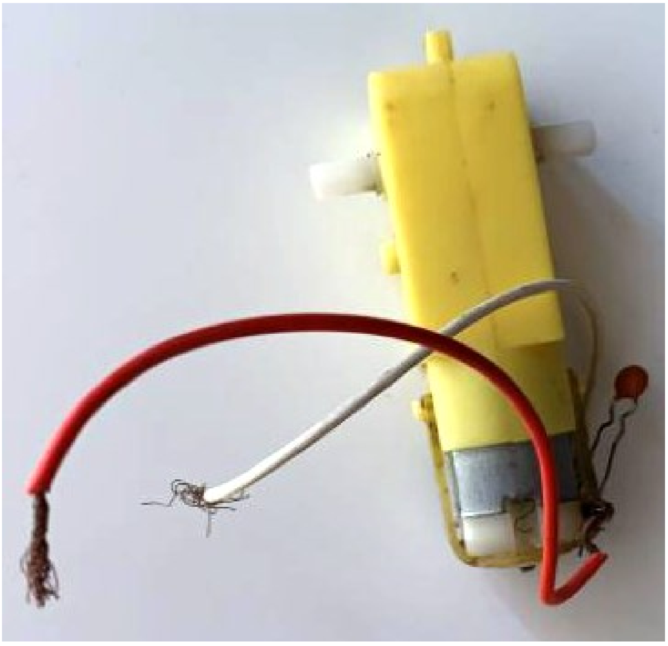


Figure 3.14: DC motor used mouth animatronics with positive and negative wiring configuration (Image created by Author).

In order to supply data, power, and to control the DC motor attached to the mouth of the teddy bear, we designed an H-bridge motor driver circuit using L239d integrated circuit (IC) [136] as shown in *Figure 3.15* was designed. An H-bridge is an electrical circuit used to apply voltage to a load, such as the DC motor, in either direction. The H-bridge is used to control the speed and direction of rotation of a DC motor. An example of an H-bridge motor driver is L239d IC

[136]. It is a dual channel H-bridge motor driver and can be used to power up to two DC motors.

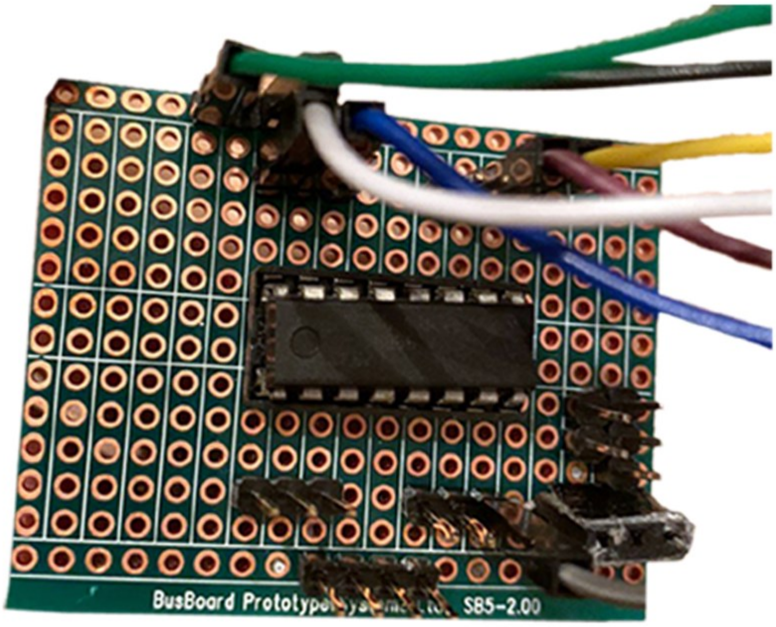


Figure 3.15: L239D H-bridge driver circuit was designed to accommodate two motors with input supply of 5V-12V (Image created by Author).

The DC motor terminals were connected to the H-bridge motor driver and the H-bridge was connected to GPIO pins 18 and 14 on the RaspberryPi and powered with a 5V DC power supply. Once the DC motor was powered, the teddy bear's mouth starts to move. A Python script titled **motor.py,** which includes Pacat, was developed. The python script runs as a software package on the RaspberryPi. It includes the Pacat command tool which monitors the raw Pulse Audio output signal from the Amazon Alexa voice service device SDK server, which are software libraries required for the DC motor to move. When executed, the Python script enables the robot to physically animate.

This automatically enables the mouth of the teddy bear to move and sync in real time with the Alexa voice service. For example, when a user asks a question using the wake word 'Alexa', the teddy bear animates its mouth in real time with the Alexa voice service to provide the user with the intended audio output response. See Python script in appendix.

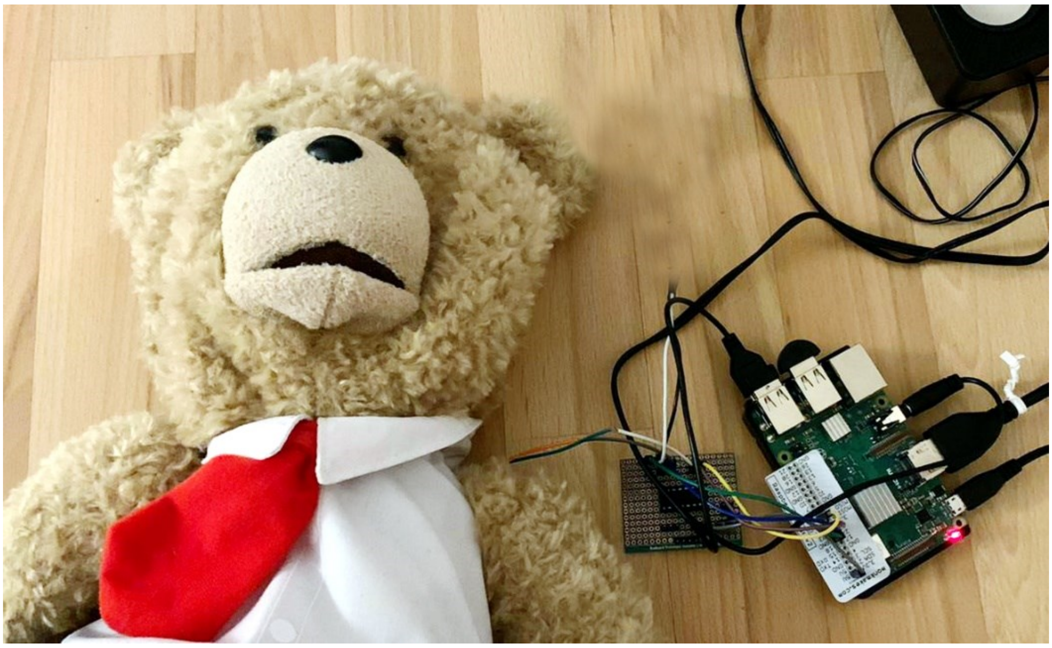


Figure 3.16: Laboratory design, setup, and the implementation of mouth motion animatronics (Image created by Author).

3.4.2.2 Arm Motion

The motion of the arm is implemented using the arm lever created in section 3.4.1 It is attached to the right and left side of the teddy bear. The servo mounted on the arm contains three wiring configurations and can be used to power and send a PWM signal from the servo motor to the RaspberryPi. The wires are colour coded in red, brown, and orange; the wiring configurations and descriptions are listed below.

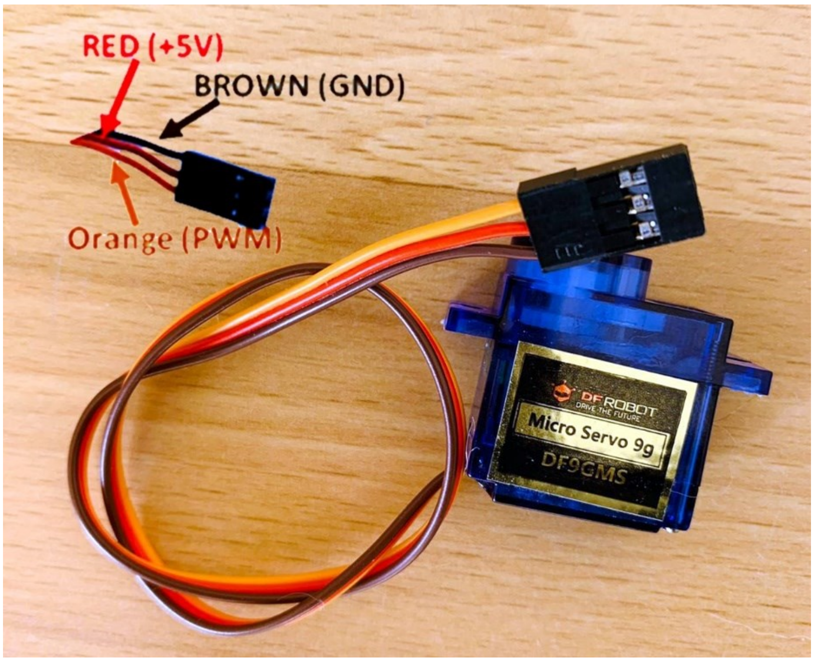


Figure 3.17: A micro servo motor 9g was÷ used to control and make the robot's arm physically move [136] (Image created by Author).

Wire color	Description
Brown	A ground terminal connected to the ground of the power supply
Red	Power terminal of the motor, typically +5V
Orange	Terminal for receiving the PWM signal to drive the motor

Table 3.5: A micro servo motor 9g terminal configuration.

Servo motors in general operate using PWM. It is used to regulate the amount of voltage delivered to a circuit. Servo motors are used to produce an analogue signal from a digital source, and it operates based on two main components: duty cycle and frequency. The duty cycle determines the fraction of time a signal is in the high state in reference to the duration of a complete cycle, and the frequency determines how fast a cycle can be completed (i.e. how fast the cycle switches between high and low states). It is an effective method for controlling the amount of power delivered to a load, in this case a servo motor. Servo motors can be controlled by sending them pulses of variable widths. The servo motor expects a pulse every

20 milliseconds (ms) and the duration of pulse applied to the signal wire of the servo motor determines its angle of rotation [136]. We can calculate the duty cycle, time, and voltage of the servo motor using the formula below.

$$Duty\ cycle = \frac{Turn\ on\ time}{Turn\ on\ time + \ turn\ off\ time} \qquad (3.4.1)$$

$$Frequency = \frac{1}{Time(t)} \ (3.5)$$

$$Time\ = Turn\ on\ Time + Turn\ off\ time \qquad (3.4.2)$$

$$Outpute\ voltage\ of\ PWM\ signal\ = Duty\ cycle\ (\%)\ x\ 5 \qquad (3.4.3)$$

For example, a 1.5ms pulse will cause the servo to rotate in a 90-degree position. Less than 1.5ms will rotate the servo in 0 degrees, and longer than 1.5ms will rotate the servo in 180 degrees [136].

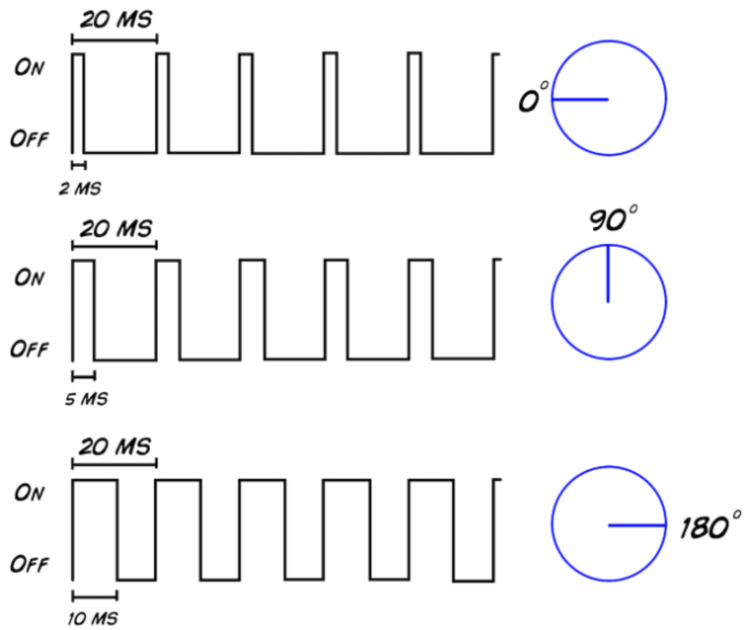


Figure 3.18: Graphic representation and angular configuration of the PWM; the duty cycle of a servo motor during operation [136].

The RaspberyPi 3B+ model has two dedicated software, Pulse Width Modulation (PWM) and GPIO pins 13 and 18. To demonstrate PWM on the RaspberryPi, the signal wire of the servo motors was connected to the GPIO pins 13 and 18 on the RaspberryPi. We developed a Python script **(motion.py)** to drive and rotate the servo motors at random angles when started. We also used the pigpio daemon to allow the servo motors to continuously rotate at random without any interruption to the Alexa voice service running on the network. See the angular configuration of the servos below.

Servo 1

```
drive_servo (18, randrange (60, 160, 2))
drive_servo (13, randrange (55, 180, 2))
time.sleep(random.random() + 0.4)
```

Servo 2

```
drive_servo (18, randrange (60, 160, 2))
drive_servo (13, randrange (55, 180, 2))
time.sleep(random.random() + 0.4)
```

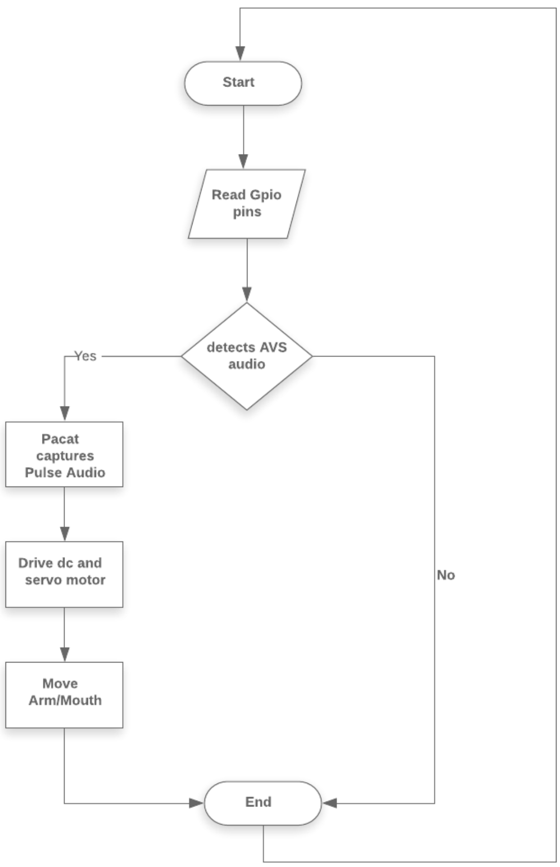


Figure 3.19:Design flow chart of the mouth/arm motion in operation (Image created by Author).

Figure 3.20: Practical application of robotic arm motion with robot arm moving randomly (Image created by Author).

3.5 PIR Sensor Device State and Attention Model

The Amazon Alexa voice service provides a library of sounds that can be combined into the device user interface manager to play a sound each time Alexa recognizes the wake word and change its state to listen. Since we have control over the Pulse Audio output for the Alexa voice service SDK, we installed this function to indicate device state with sounds, which occurs when the robot physically animates and when it is in a listening or speaking state. Secondly, we introduced a new, third state, called idle/standby state functionality, so that the robot can detect objects around it and remain in standby state. For example, when a user is in proximity with the robot, it physically animates its arms to indicate to the user it is still active (it could be interpreted as a "greeting" or "acknowledging a person's presence" by a young user) and when the user moves away, the robot goes to an idle state. This function was created as an innovative way to indicate the standby state and gain the user's attention. The function was implemented using a passive infrared (PIR) motion sensor.

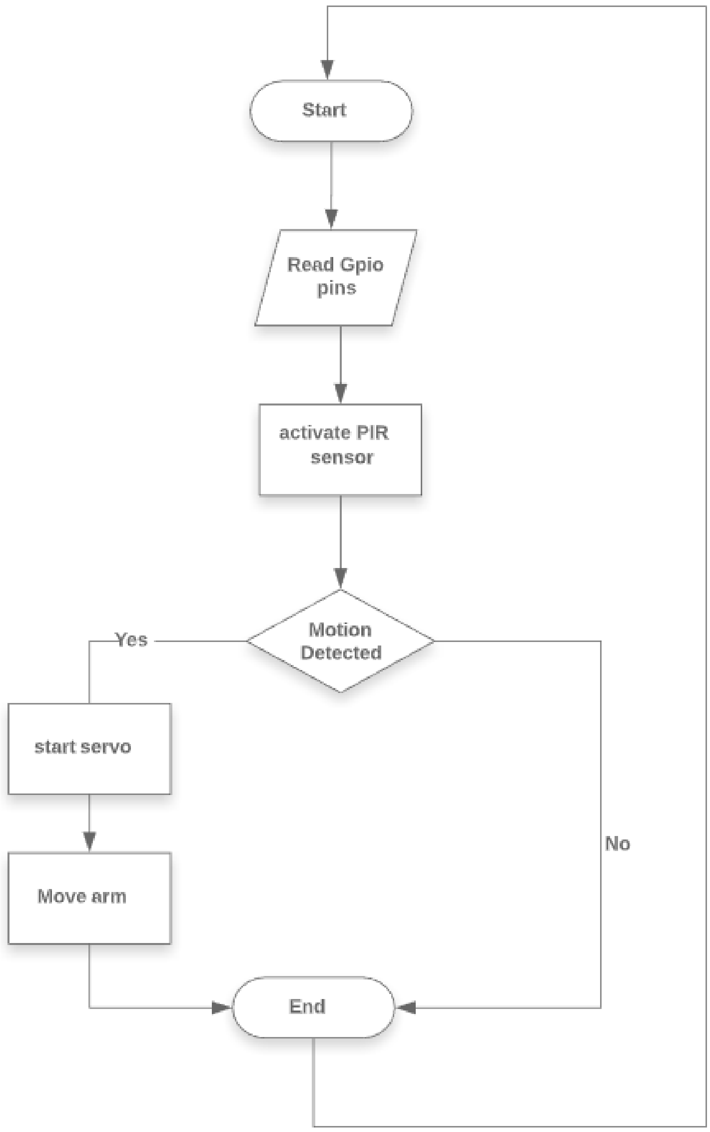


Figure 3.21: Design flow chart of device state PIR motion and attention driver (Image created by Author).

To demonstrate and implement the innovative standby or idle state, we programmed the PIR sensor, connected it to GPIO pin 19 on the RaspberryPi, and supplied power to it using +5V DC and ground pins. It was programmed using a separate Python script (**motion sensor**) with the servo motor. We used the PIR motion sensor to drive the servo motor in the robot to rotate randomly when motion is detected and to stop when no motion is detected, which consequently causes the arm of the robot to rotate relative to the PIR sensor.

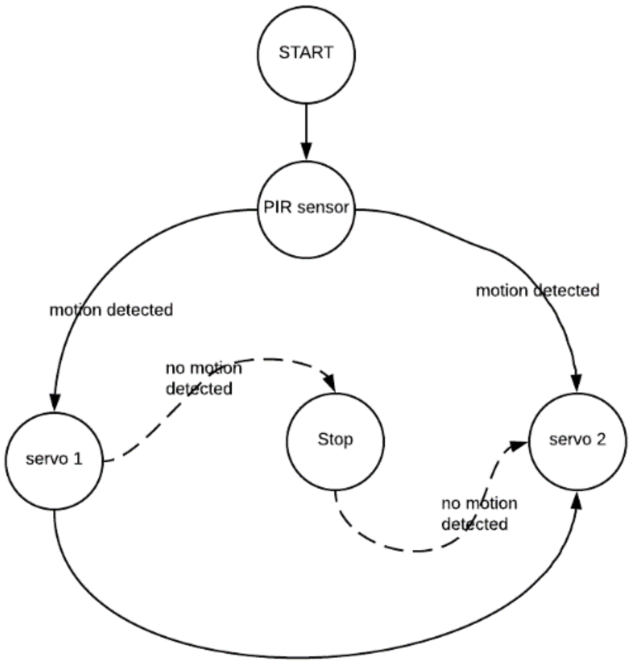


Figure 3.22: PIR motion sensor device state and attention model state diagram (Image created by Author).

Figure 3.23: Representation and practical application of PIR motion sensor with the Teddy Bear robotic prototype (Image created by Author).

3.6 Power Supply

The initial power supply for our prototype used a rechargeable battery-operated power supply unit. However, due to limited resources and cost, an alternative was designed, and the DC power supply was connected directly to a power source via a USB cable.

The RaspberryPi operates with a steady voltage of 5V and a current of 2.5A and was connected to a DC power, and the RaspberryPi powers both the Bluetooth microphone and the speaker. The DC and servo motors operate with a voltage of 5V and a current of 2A. The PIR motion sensor operates with a variable voltage of 4V to 12V and was connected directly to a USB connected DC power supply. To connect the PIR motion sensor, DC and servo motors, we developed an electric Busbar and a USB power cable connection to provide regulated power to the Busbar. We strip and connect one end of the USB cable to the Busbar and the other to a power supply. (See Figure 3.24 below for power supply design setup). The final circuit design was soldered onto a printed circuit board (PCB).

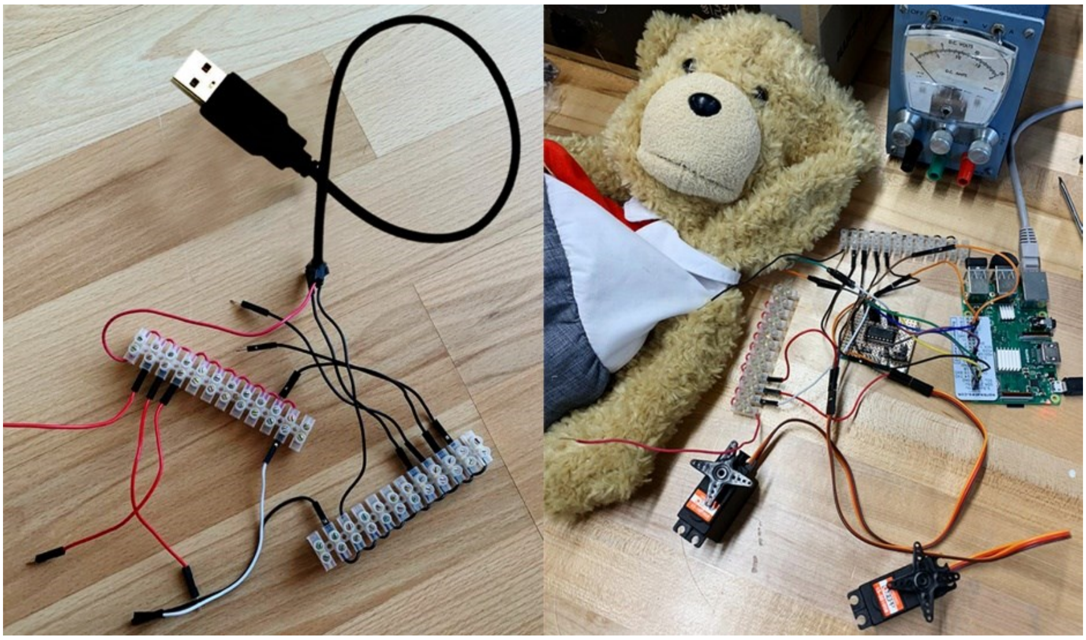


Figure 3.24: Design setup and testing of power supply unit using a Busbar and DC power supply – USB cable connects actuators and PIR sensor to Busbar and Busbar connects to regulated DC power supply (Image created by Author).

3.7 Use Case Study

In this section we discuss and compare the advantages of our design of the social robot prototype to the Lexa-Bear robot and other closely related robots mentioned in this research work. The case study is used to validate our design.

3.7.1 Lexa-Bear

The Lexa-Bear robot is not commercially available for purchase as it is currently a subject of an intellectual property dispute [152]. Therefore, there is no available review on its impact with ASD subjects. However a video review, available at [26], shows that it was designed for therapeutic purposes associated with children with autism. The Lexa-Bear can hear and speak to its subjects, but it need to be connected to an Echo Dot speaker to do so. It can engage kids in social interaction and play games with them. One of the subject's recorded responses was "I have never seen a Bear that could talk, it thought it was really cool".

3.7.2 JIBO

JIBO is a social robot developed for home and therapeutic applications. JIBO has no arms and legs, only two joints, but it can move its rotund body in 360 degrees and is also equipped with facial recognition technology. JIBO has been used in many case studies for example, it was used in an experiment by Brian Scassellati [153] to give children a long-term relationship with JIBO. For 30 minutes each day in a 30-day study, the children sat next to their parents or other family members to interact and play games with JIBO. The games were based on a clinical therapy practice for improving different social skills and emotional understanding. The games focused on developing skills such as understanding a concept from someone else's perspective and completing tasks in a sequence. For instance, in a game called "Rocket" that was played on a computer tablet, the child and the caregiver take turns building a rocket ship by pulling parts together around the screen. The screen is then reset to hide this design, and the first player must explain to the second player how the design is recreated.

Throughout the games, JIBO models good social behavior by concentrating on the child or the caretaker and orienting its body toward them. It also asks the child to do the same. At several points, the robot would call the child by name, asking them to engage with their caregiver by looking at them. After each session, the system's software changed the game's difficulty based on the child's performance. Caregiver's reports showed that the social skills of all 12 children improved over the course of the study [153].

Another study by Professor Lundy Lewis also used JIBO for social reinforcement in applied behavioural analysis with children with autism. The experiment was set to determine whether social robots offer additional advantages to the existing methods of interacting, and the results showed that the children enjoyed playing with robots.

3.7.3 PARO

PARO is used to administer animal therapy to patients in a medical environment. PARO provides key benefits such as reducing the negative emotional and behavioural symptoms and patterns, improving social engagement, and promoting positive mood and quality of care experience.

PARO responds to interactions with a user as if it is alive by moving its head and legs, making sounds, and imitating the voice of a real baby harp seal to show a preferred behaviour. An elderly lady living alone made the following comment, "PARO is lovely, it helped me reduce feelings of loneliness following the death of my husband". She mentions feeling calm and comforted when interacting with PARO [154]. Another user in a video review that can be found at [155] cites that users do not truly think that PARO is a real animal, however, users treat it as if it was real because it promotes a positive feeling.

Although PARO offers a key technological opportunity in supporting dementia care for elderly people and managing difficult behavioral symptoms, the use of PARO in a care setting remains low. A major barrier to the adoption of the technology is the initial cost of purchasing the device which is approximately $6,400 USD.

3.7.4 Our Design Prototype

In a typical therapeutic setting, a user can engage and interact with the robot using voice commands. They have to say the wake word, “Alexa”, and then continue stating any directive they have in the form of questions or conversation. For example, when a user asks, “Alexa, what is the time?”, the microphone captures the audio signal and sends it to the Alexa voice service SDK. The AVS SDK listens, recognizes, and processes the wake word request and responds with an audio output generated by the speaker built in the device. Figure 3.26, shows an example of the flow of information in the proposed robot under such a scenario.

The user can respond with as many questions/commands he/she wishes to express, with the AVS responding accordingly. The robot will remain in an idle mode when there is no request. The robot can respond to the user’s command/request by animating its arm and mouth, which are connected to a DC and servo motor. As mentioned earlier, the robot has been equipped with a PIR motion sensor. Its presence is useful in the absence of verbal interaction with the robot and it enables the robot to detect motion within its field of view. After the robot has sensed motion, it moves its hands in order to attract attention. If the user intends to continue the conversion, he/she can do so by using the wake word, “Alexa”, again.

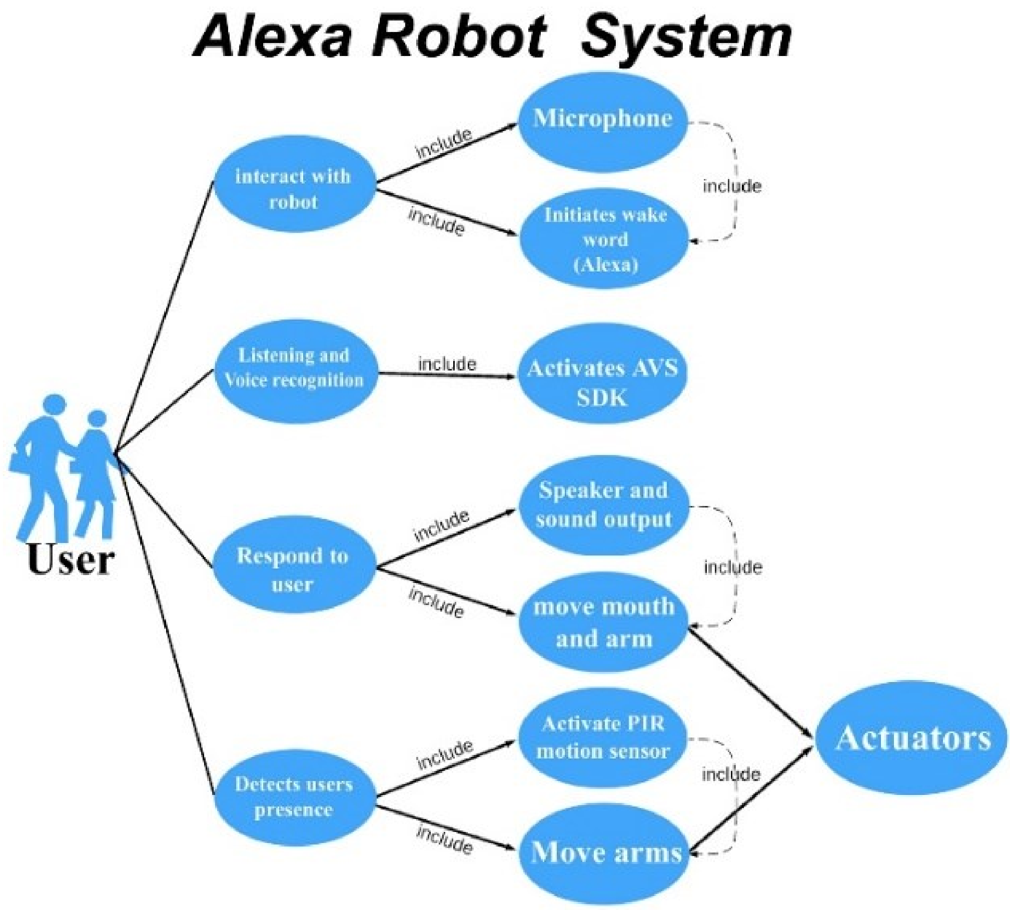


Figure 3.25: Sample use case and application of our robot (Image created by Author).

Figure 3.26 describes in a flow-chart format a sample conversation and the intended actions performed by the robot.

User	Alexa Robot Actions
Alexa, what is the time?	The time is 11am + move arms and mouth
Voice interaction + motion detected	PIR sensor detects motion + move arms
No voice interaction + motion detected	The robot moves for 10 secs + Idle state
No voice interaction + no motion detected	Remain in an idle state until turned off or detects motion.

Table 3.6: Alexa robot sample dialog and actions.

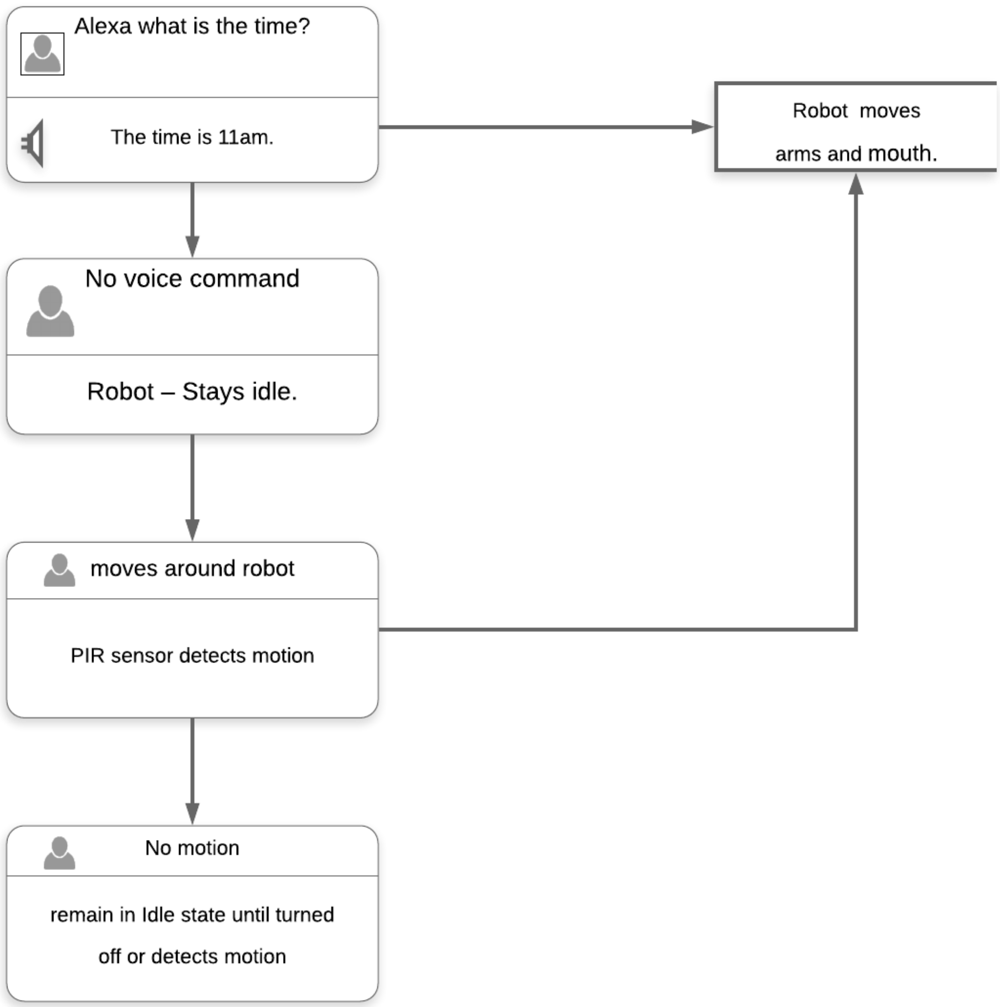


Figure 3.26: flow of conversation and actions that can be performed with our robot prototype (Image created by Author).

Chapter 4: Performance Evaluation

In this chapter, we discuss the behavior and performance of our prototype. Evaluation was planned to be carried out in two phases.

In phase one, we carried out a series of tests to validate the performance of each component used in the design. We observed and recorded any errors as well as made the required modifications when needed to ensure the robot was working as expected.

4.1 Testing Phase 1

4.1.1 Test 1– Amazon Alexa Voice Service Algorithm Testing

To test the performance and reliability of the AVS on the RaspberryPi, we connected a speaker and a microphone and carried out eleven (11) voice test interactions with the AVS sample App. We recorded the time intervals it takes for the AVS to respond to a given command/directive, including how easy it is to understand a user's voice and give the desired output.

Figure 4.1: Practical application and testing of Amazon Alexa voice service algorithm (Image created by Author).

A sample of tests were carried out and the results obtained are shown in Table 4.1. This is a typical and representative set; all tests provided very similar results.

No of Tests	Voice Interactions (Input)	Voice response (Output)	Response Time (secs)
1	"Alexa, what is the time?"	The time is 5:24pm.	5 secs
2	"Alexa, tell me a story?"	A story about the rock.	10 secs
3	"Alexa, when was Apple (computer) invented?"	Apple was founded on April 1st, 1976 by Steve Jobs, Steve Wozniak, and Ronald Wayne, and it is 44 years Old.	6 secs
4	"Alexa, how old is Queen Elizabeth?"	Queen Elizabeth the II is 94 years old and was born on April 21st, 1926.	6 secs
5	"Alexa, what is the formula for standard deviation?"	Standard deviation is equal to the square root of variance, which is the average of the squared differences between each value and the mean.	8 secs
6	"Alexa, what is 10 to the power of 308?"	10 to the power of 308 is 1 times 10 to the 308th power.	8 secs
7	"Alexa, what is three percent of fifty thousand dollars?"	3% of $50,000 USD is $1,500 USD.	10 secs
8	"Alexa, what is your occupation?"	Trying to say, "tell me a short joke or tell me about Mars."	8 secs

9	"Alexa, tell me about autism?"	Here is the Wikipedia article on autism…. Would you like me to keep reading?	8 secs
10	"Alexa, how many children are affected with autism in Canada?"	Sorry, I don't know that.	10 secs
11	"Alexa, how do you say hello in French?"	Hello in French is Bonjour.	9 secs

Table 4.1: Testing of Amazon Alexa voice service Algorithm

From the totality of the results, we drew the following conclusions:

a) When the wake word, "Alexa", is activated by voice, the response time it takes to deliver an output was higher than 5 secs but rarely exceeded 8 secs depending on the kind of voice instruction that was given. This goes to show that a poor internet network connection will deliver a longer response output or no response at all.

b) If Alexa is responding to a directive with the wrong answer, a user can say, "Alexa stop", to stop or clear a conversation with the AVS.

c) Alexa takes a longer time to respond to mathematical calculations and tell a story.

d) Alexa can engage a user by asking them to follow up on questions as we can see in the test interaction - 8.

e) Alexa responds to questions/commands it does not understand by providing suggestions to the user in order to understand the user.

f) Alexa recognizes commands/questions it receives as a string of text and responds in plain English depending on the language selected during the device installation and registration process. It supports multiple languages.

g) As we can see in test interaction - 9, there are certain questions that Alexa cannot answer. For example, for Alexa to identify a user's location, it requires the user to manually give it permission to record their address information and store it in its database.

4.1.1.1 Test 1– Background Noise and Interference

Sounds such as TVs, radios, or music players are most likely to interfere or be misinterpreted as Alexa commands. Learning to identify the distinctive characteristics of individual sounds is a good way to ensure an accurate, automatic speech recognition for Alexa's voice service. To detect commands in the presence of background noise, Alexa uses microphone arrays to detect voice activation commands at a listening range of 1 to 3m (3-9ft) and signal to noise ratio (SNR) for normal speech of less than 35dB, given an outside noise of 70dB. It can be said that the lower the noise produced by a microphone, the better the speech recognition.

The following solution can be implemented to reduce the influence of unwanted background noise that may affect the proposed voice activated robot design prototype;

i. When a user says the Wake word (Alexa), they should ensure that there is nothing interfering or blocking the device from hearing the user's voice commands in any direction.

ii. There is a way to teach the Amazon Alexa voice service software to learn to recognise and understand a user's voice. This feature is known as "Recognised voices". This requires a voice profile to be created, which enables Alexa to learn the user's voice, call the user by name, and provide enhanced personalisation including ignoring other voices or background noise. This feature can be accessed from Amazon AVS device application settings.

iii. The use of Cirrus voice capture technology [156]. This is a high-performance sound algorithm that can be integrated to enhance voice interaction with voice activated digital assistants. It allows the user to suppress background noise and interference and give the voice assistants such as Alexa, more accurate and reliable interactions. Its microphone covers an ultra low noise and wide dynamic range of 130dB. This allows it to block noise that would otherwise interfere with Alexa, and therefore improves voice command detection in both quiet and noisy environments even if users are several meters away.

4.1.2 Test 2 – Voice Interaction Algorithm and Mouth Motion Testing

Here, we tested the AVS interaction algorithm with the mouth motion of the robot. To carry out this test, we executed the AVS program simultaneously with the mouth motion Python script which controls and activates the DC motor to move the mouth of the robot. We tested the mouth functions of the robot by activating the wake word followed by a command or question. We particularly paid attention to how the mouth synchronized in real time with AVS during a conversation with the robot. We controlled the direction of the DC motor rotation by applying either a logic HIGH (5 Volts) or logic LOW (Ground) to the direction of the control pins on each channel of the H-bridge. The results show how the robot opens and closes its mouth in real time while responding to commands or questions.

PIN 1	PIN 2	Action
Low - 0	Low - 0	Motor off
High - 1	Low - 0	Mouth open
Low - 0	High - 1	Mouth lose
High - 1	High - 1	Motor off

Table 4.2: Directional and angular control and configuration of the DC motor.

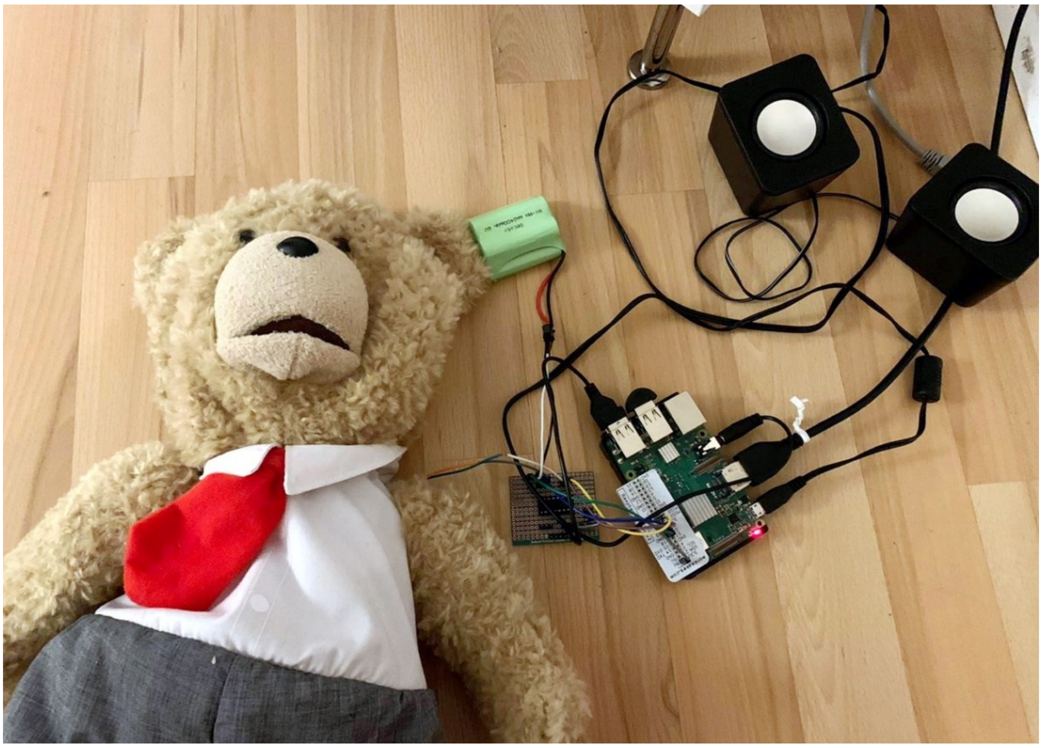


Figure 4.2: Practical application to confirm Alexa voice service can physically animate with mouth during voice interaction (Image created by Author).

4.1.3 Test 3 – Arm Animatronics and Motion Testing

Here, we tested the arm animatronics of our prototype by mounting the two servo motors on a 3D printed arm lever. We mounted the two servos on the left and right side of the 3D printed arm lever and connected it to the RaspberryPi GPIO pins 18 and a battery power supply. To test this feature, we executed the Python script, which activates the two servo motors that creates the arm motion.

In our first test we set the angle of rotation of the right and left servo motors from 0 to 90 and 180 degrees, clockwise and anticlockwise receptively. The result showed the motors only create an upwards and downwards arm motion (i.e. 0 to 90 and 180 and then goes to sleep at 0 degrees). This did not satisfy our requirements, which is why we carried out another test by modifying the Python script to include and execute a random software library. This second test included a variety of random numbers generated to determine the angle of movement of the 2 servo motors (e.g. randrange (60, 160, 2)) and the results indicated that the random library enabled the arms to continuously move arbitrarily as expected.

We also experienced a problem of jitter, meaning that the servos were shaking, and this was because of the pulses generated by the RaspberryPi. This problem occurred because the RaspberryPi software GPIO library executed in the Python script uses software timing for PWM (Pulse Width Modulation), and the exact timing of these pulses is important to achieve a smooth and accurate arm motion. We observed that the GPIO library used in our program was not suitable for controlling two or more servo motors as it cannot guarantee the precision of pulses.

In order to solve this problem, we can use one of the following two options:

i. By connecting the two servo motors directly to the two dedicated hardware PWM pin channels available by default on the RaspberryPi 3B+ model (i.e. Pin 18 & 13), which executes the software pigpio library in the Python script to control the motion of the servo instead of using the software GPIO library.

ii. By using external hardware to generate the PWM.

Since we were only working with two servo motors, option (i) was suitable for our application. Therefore, we reconnected the two-servo motor to GPIO Pins (18 and 13) receptively on the RaspberryPi and also included the pigpio library in our Python script and the jitter problem was automatically eliminated. The two servos were mounted on the 3D printed part connected to the right and left arm of our teddy bear and results confirmed the expected output.

Figure 4.3: Practical application and testing of 3D-printed Arm animatronics and motion framework (Image created by Author).

4.1.4 Test 4 – PIR Sensor Device State Testing

To test the PIR sensor device state, we executed the PIR sensor Python script and initiated a voice interaction with the robot. During the conversation the robot sensed motion and moved its arms. To specifically test the idle state, we stopped the interaction with the AVS and allowed the robot to go into the idle state. While the robot was dormant, we performed various tests on a set of events while in front of the motion sensor and recorded the results.

Table 4.3, shows a series of test actions that were carried out and their results.

a) Test performed during the day.

Events	Distance (m)	Motion detected	Sensitivity (High/Low)	Response hold time (secs)
Wave hand	0.8	Yes	High	7 secs
Raise hand	0.7	Yes	High	7 secs
Stand Up	0.9	Yes	High	8 secs
Walk close to the robot	2.35	Yes	High	8 secs
Continuous movement	0.7	Yes	High	>10 secs
Walk away from the robot	2.5	No	Low	0

Table 4.3: Daytime testing of the PIR motion sensor attention model.

b) Test carried out at night

Events	Distance (m)	Motion detected	Sensitivity (High/Low)	Response hold time (secs)
Wave hand	0.8	Yes	High	8 secs
Raise hand	0.7	Yes	High	7 secs
Stand Up	0.9	Yes	High	7 secs
Walk close to the robot	2.35	Yes	High	7 secs
Continuous movement	0.7	Yes	High	>10 secs
Walk away from the robot	2.5	No	Low	0

Table 4.4: Night-time testing of PIR motion sensor attention model.

From the results above, we can conclude the following:

a) The presence of light sources does not affect the performance of the PIR sensor. This was expected since PIR works in the infrared spectrum. Since the tests were conducted inside, the infrared component of solar radiation was not strong enough to affect the results during the day. Also, modern interior lighting sources (e.g. fluorescent or Light Emitted Diodes) produce “cold” light, meaning its content in the infrared spectrum is small. We did not conduct tests outside during the daytime, since use of the robot in the open is not a recommended approach.
b) Average response and hold time are approximately 7 secs.
c) No motion was detected when a person was standing at a distance of 2.5m.
d) If no motion is detected, the robot remained in an idle state and vice versa.
e) Lastly, it is important to mention that in a scenario where there is no voice interaction with a user and motion is detected, the robot will not move its arm continuously, but only approximately for about 10 secs and then it will go into sleep or idle mode until it detects motion again.

Figure 4.4: Laboratory testing and practical application of PIR sensor device state and attention model of the robot’s prototype framework (Image created by Author).

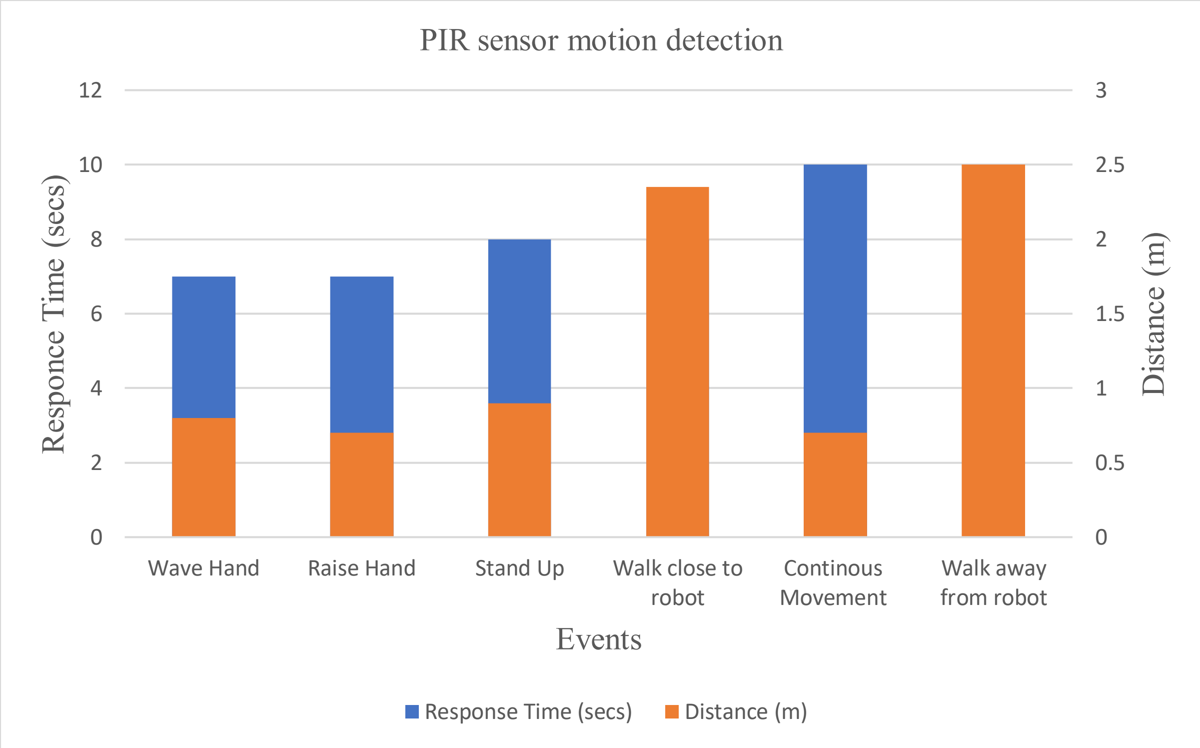


Figure 4.5: Time responses and distance measurement of PIR sensor device state and attention model with Amazon Alexa voice service (Image created by Author).

4.1.5 Test 6 – Final Design Assembly

In order to integrate all components into a complete prototype, we permanently soldered all the design components together onto a PCB board and inserted it in the teddy bear. We also configured the software packages running on the RaspberryPi to the output so that it is automatically activated as soon as the robot is turned on and connects to a default WIFI and through that to the internet. We tested and confirmed all components of our design, and the prototype worked as expected. The only drawback experienced during the process, was that the robot could not be automatically connected to the internet. To establish internet connectivity with the robot, we can connect WIFI via secure shell (SSH) network protocol or modify the WPA supplicant to add new WIFI connections. (see further information in Appendix D).

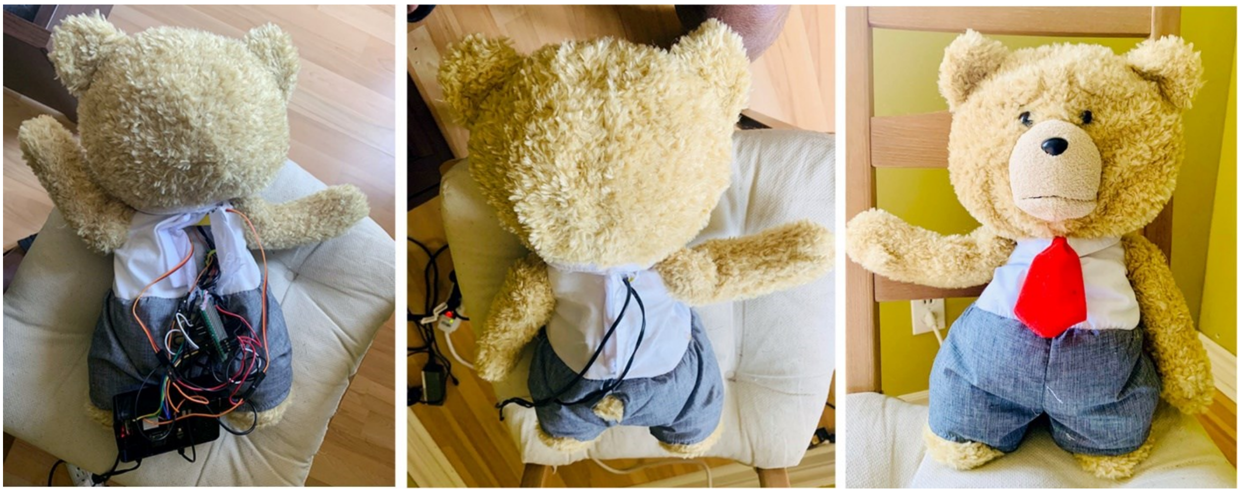


Figure 4.6: Complete assembly and packaging of the robot's circuit inside the teddy bear body (Image created by Author).

The table below shows a comparison of the features and the functions our robot system to the Lexa-Bear and other robots.

Features	Our design prototype	Lexa-Bear Robot	JIBO	PARO
Autonomous CPU	Yes	No	Yes	Yes
Voice Technology	Alexa	Alexa	Truly Natural	Baby Harp seal sounds
Animatronics	Arm/Mouth	Mouth	Spin 360 degrees	Head/legs
Power supply	USB	Power Adapter	Rechargeable Battery	Battery
Response to motion	Yes	No	Yes	Yes
Attention Technology	Yes	No	Yes	Yes
Price	Approximately $235 CAD	Not available	$899USD	$6,400 USD

Table 4.5: Evaluation of Engineering effort and contribution.

We have established that our robot provides an enhanced set of features compared to Lexa-Bear robot. The cost of the design prototype is low, approximately $235 CAD, which makes the robot affordable for the general population. It is expected that with the availability of a comprehensive treatment curriculum, which can be carried out not only by professionals but by parents and caregivers as well, our social robot will become a useful tool in the treatment of children with ASD and specifically in the development of social and communication skills.

4.1.6 Test 6 – Power Supply

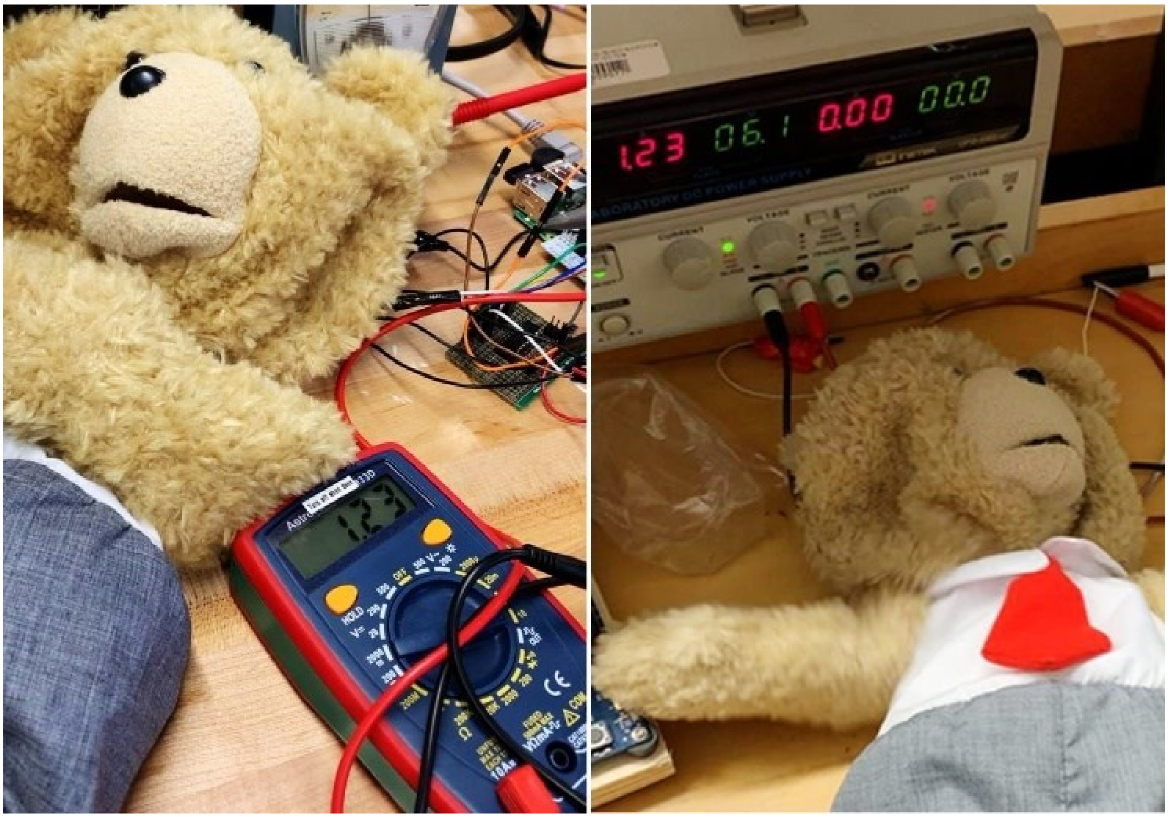


Figure 4.7: Practical application of the robot; prototype is connected to a DC power supply and includes the measurement of voltage, current, and power consumption using a multimeter (Image created by Author).

Figure 4.7 above shows our robotic prototype, including all its interconnected components such as DC and servo motors, PIR sensor, etc. as connected to a laboratory DC power supply. This design procedure was performed because of a lack of resources and to accommodate the cost of a rechargeable battery-operated system as an alternative power supply use to satisfy the design objectives. The RaspberryPi was connected to a separate DC power source, therefore, no measurements were needed.

The robot operates at a DC voltage and current measurement of:

$$Voltage\ (V) = 6.1V$$

$$Current\ (I) = 1.23A$$

The DC Electrical power consumed by circuit can be obtained using the following equation,

$$Power\ (P) = I\ x\ V\ (4.1)$$

Therefore, Electrical Power (P),

$$Power\ (P) = 6.1\ x\ 1.023$$

$$P = 7.5\ watts\ (W)$$

The following observation was made from the power measurement results above:

i. The actuators (DC and servo motors) consume the most significant amount of power i.e. The voltage of 2V and current of 2A leading to a power of 4 watts as compared other interconnected devices.
ii. The load connected to the power supply determines the ratio of current to volt at the connection terminals.
iii. The voltage supplied determines the current and vice versa.
iv. An increase in voltage leads to increase in current, thereby leading to increased power.

4.2 Testing Phase 2

The purpose of the second phase was to assess the effectiveness of our social robot prototype as an actual treatment tool. It was scheduled to be used in actual treatment sessions of autistic children, carried out by Prof. Lewis in the presence of expert therapists. However, due to the COVID-19 pandemic, the activity had to be postponed as the testing locations were closed and the test is yet to be performed. As a result, we cannot fully determine the impact of our robot on children with ASD.

4.3 Robot Safety

Our robot prototype consists of the following safety guidelines:

a) It was ensured that there was no presence of electrical wiring or components that would cause any form of danger to a user.

b) Wiring and components were safely hidden out of reach to minimize pinch points.

c) The animatronics and moving components of the robot prototype were designed to withstand some mishandling and mistreatment without causing any harm.

d) We ensure that parts can be easily replaced and reassembled in case they break.

e) We advise that the teddy bear should be regularly sanitized after each use.

f) We recommend that in a therapy session, therapists should support the user to safely handle the robot.

4.4 Proposed Therapy Protocol

To test the effectiveness of our proposed robot prototype, it can be considered for use in a child-robot assisted therapy session/experiment that will inspire socialization and communication with the robot. The user can use voice commands (Alexa) to ask questions on any area of interest, for example, in a social interaction experiment between a child with autism and a therapist.

The therapy protocol experiment may be conducted as follows:

a) The robot, along with another social robot, is placed in a room with an ASD subject in a child-robot assisted therapy session setup by a therapist.

b) The therapist then performs and times a sample of interactions with the designed robot prototype using the voice technology (Alexa) commands and encourages the ASD subject to engage with the robot.

c) The therapist then performs an observation preference assessment on the ASD subject to determine which robot the ASD subject is attracted to and likes to engage with the most.

d) Next, the therapist tags the robot with which the ASD subject engages the most during each interval, where "engage" is defined as speaking to or touching the robot.

e) Finally, the therapist records and determines the percentage of time that the ASD subject engages with the robot and calculates the engagement intervals.

Chapter 5: Conclusion and Future work

In this research, we have successfully designed and produced an enhanced low-cost social companion robot prototype.

The design prototype consists of the following features:

- A microcontroller
- The ability to receive and interact with a user (ASD subjects) with voice activated commands using the Amazon Alexa voice service and the wake word (Alexa).
- The ability to physically animate with voice commands and sounds when providing answers.
- The ability to indicate device state and capture the user's attention using PIR sensor technology combined with actuators.
- It is relatively safe to handle and can withstand mishandling and mistreatment without causing any harm or injury, and the electrical components are safely hidden out of reach to minimize pinch points.
- Finally, with low design costs at approximately $230, this makes the robot relatively cheap and affordable for low-income families. Table 3.1÷ shows that the RaspberryPi and teddy incur the most significant cost to the design of the robotic prototype. Therefore, an alternative option to consider in place of the teddy bear would be a 3D printed plastic robotic chassis/body.

The design features of our prototype are in line with the design objectives in Prof. Lundy Lewis's research, and these features are considered to be useful in training children with ASD to acquire social and language skills. The robot's features, such as its ability to animate (arms and mouth) with voice-activated sounds and conversation and detect movements, make the design prototype appear more realistic.

We expect that the robot will be used in actual therapy sessions with children with ASD. It is also our expectation that with the design of a proper curriculum, parents or guardians of children with ASD will be able to be perform frequent treatment sessions at home.

Some design limitations and areas of future research to improve this design prototype includes the following:

- The design of battery-operated power supply unit to handle the robot's power supply requirements, as well as the ability to recharge the battery when it is low. This feature will make the robot safer to use.
- It is said that robots with fur material are being phased out and are no longer acceptable in therapeutic environments especially one with ASD subjects. This is because they easily attract dirt which can be transferred from one child to another, and they are difficult to clean or disinfect. Therefore, for future design of the body/chassis of the robot, we recommend the use of a 3D printed plastic prototype, as they are considered safe and acceptable and can easily be sanitized and cleaned.
- A network connectivity module so that the robot can automatically be connected to different WIFI networks at anytime.
- Investigate the use of light from Amazon Alexa voice service instead of sound to make the robot physically animate.
- An easily accessible emergency stop button or switch that allows the therapist to quickly deactivate the robot in the case of an emergency or if the robot malfunctions.
- Finally, a method of functionally testing the robot with a defined therapy protocol with ASD subjects as suggested in section 0 with the presence of an expert. A therapy session with Prof. Lundy Lewis, which was not possible due to COVID-19 pandemic, will be very useful to measure the impact of this research on children with autism.

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Appendix

A. Installation of the Alexa voice service device SDK on the RaspberryPi

i. Visit the website **developer.amazon.com** to register for an Amazon developer account and sign in.

i. Click **Alexa voice service** and create a new **Product**.

ii. Fill in the product information and product type (select device with Alexa built-in).

iii. Create a new **LWA** (Login With Amazon) **security profile** and fill the required details.

iv. Click on **product details** menu and select **security profile.**

v. Select **other devices and platform** options and input **client ID** information (e.g. prototype or RaspberryPi).

vi. Click "**Generate ID**" to get a client ID with the option to download it.

vii. Click on "Download" to download the **Config.json** file (contains **client ID**, **client secret,** and **Amazon ID** information) onto the RaspberryPi.

viii. Agree to the AVS agreement and program requirements.

ix. Click on **Finish** to create the Alexa **Product**.

x. Copy and paste the **config.json** file into the `home/pi` directory on the RaspberryPi.

xi. Open a new terminal window on the RaspberryPi

xii. Use the commands below to build the AVS device SDK configuration script

```
wget https://raw.githubusercontent.com/alexa/avs-device-sdk/master/tools/Install/setup.sh \
wget https://raw.githubusercontent.com/alexa/avs-device-sdk/master/tools/Install/genConfig.sh \
wget https://raw.githubusercontent.com/alexa/avs-device-sdk/master/tools/Install/pi.sh
```

xiii. Run the **setup.sh** install script command to build the Alexa voice service **SampleApp** using the **config.json file** and default device serial number (1234).

```
cd /home/pi/
sudo bash setup.sh config.json [-s 1234]
```

xiv. Agree to the terms and conditions for third-party libraries and sensory wake word.

xv. Complete the configuration/build and launch the **SampleApp**.

xvi. Start the **SampleApp** to authenticate the device using the command below

```
sudo bash startsample.sh
```

xvii. Get and submit the Alexa authorisation code.

xviii. Connect the Bluetooth microphone and speaker to the RaspberryPi.

xix. Start the SampleApp (**sudo bash startsample.sh**) to talk with Alexa using the wake word, “Alexa”.

xx. Modify the bashrc file to include the sudo bash startsample.sh command and configure the RaspberryPi boot options to automatically start the Alexa SampleApp as text console; automatically log in as ‘pi’ user.

B. Mouth and Arm motion Python Script

```
import RaspberryPi.GPIO as GPIO

import struct

import subprocess

import time

import random

import threading

from random import randrange

from servo_driver import *

import sys

MOUTH_PIN = 24

PIR_PIN = 19

PA_SOURCE = "alsa_output.platform-soc_audio.analog-stereo.monitor"

PA_FORMAT = "u8" # 8 bits per sample

PA_CHANNELS = 1 # Mono

PA_RATE = 2000 # Hz

PA_BUFFER = 32 # frames for a latency of 64 ms

SAMPLE_THRESHOLD = 4

is_up = False

is_motion = False

GPIO.setwarnings(False)

GPIO.setmode(GPIO.BCM)

GPIO.setup(MOUTH_PIN, GPIO.OUT, initial=GPIO.LOW)

GPIO.setup(PIR_PIN, GPIO.IN)

GPIO.add_event_detect(PIR_PIN, GPIO.RISING)
```

```
def drive_motion():
    while True:
        i=GPIO.input(PIR_PIN)
        if i==0:
            is_motion = False
            print("Nothing Detected")
        else:
            if not is_up:
                is_motion = True
                print("Motion Detected")
                j = 3
                while j > 0 :
                    drive_servo(18,randrange(60, 160, 2))
                    drive_servo(13,randrange(55, 180, 2))
                    time.sleep(random.random() + 0.4)
                    drive_servo(18,randrange(60, 160, 2))
                    drive_servo(13,randrange(55, 180, 2))
                    time.sleep(random.random() + 0.4)
                    j -= 1

                drive_servo(18,60)
                drive_servo(13,180)
                time.sleep(3)
        #turn_off(13)
        #turn_off(18)
```

```
        print("end of loop")
def arm_control():
    while True:
        if is_up:
            drive_servo(18,randrange(60, 160, 2))
            drive_servo(13,randrange(55, 180, 2))
            time.sleep(random.random() + 0.3)
        else:
            if is_motion:
                drive_servo(18,0)
                drive_servo(13,180)
                #turn_off(13)
                #turn_off(18)
# Capture audio using `pacat` -- PyAudio looked like a cleaner choice but
# doesn't support capturing monitor devices, so it can't be used to capture
# system output.
parec = subprocess.Popen(["/usr/bin/pacat", "--record", "--device="+PA_SOURCE,
    "--rate="+str(PA_RATE), "--channels="+str(PA_CHANNELS),
    "--format="+PA_FORMAT, "--latency="+str(PA_BUFFER)], stdout=subprocess.PIPE)
def mouth_motion():
    while not parec.stdout.closed:
        # Mono audio with 1 byte per sample makes parsing trivial
        sample = ord(parec.stdout.read(1)) - 128
        print(abs(sample) > SAMPLE_THRESHOLD)
        if abs(sample) > SAMPLE_THRESHOLD:
```

```
            GPIO.output(MOUTH_PIN, 1)
            is_up = True
        else:
            GPIO.output(MOUTH_PIN, 0)
            is_up = False
motion_thread = threading.Thread(target=drive_motion)
motion_thread.start()
#arm_thread = threading.Thread(target=arm_control)
#arm_thread.start()
mouth_thread = threading.Thread(target=mouth_motion)
mouth_thread.start()
```

C. Motion Sensor Python Script

```
import RaspberryPi.GPIO as GPIO

import time

import random

import multiprocessing

from random import randrange

from servo_driver import *

GPIO.setmode(GPIO.BCM)

PIR_PIN = 19

GPIO.setup(PIR_PIN, GPIO.IN)

time.sleep(2)

GPIO.add_event_detect(PIR_PIN, GPIO.RISING)

print("Started")

is_motion = False

def drive_motion():

    while True:

        i=GPIO.input(PIR_PIN)

        if i==0:

            is_motion = False

            print("Nothing Detected")

        else:

            is_motion = True

            print("Motion Detected")

            j = 3

            while j > 0 :
```

```
            drive_servo(18,randrange(0, 180, 2))
            drive_servo(13,randrange(55, 180, 2))
            time.sleep(random.random() + 0.15)

            drive_servo(18,randrange(0, 180, 2))
            drive_servo(13,randrange(55, 180, 2))
            time.sleep(random.random() + 0.15)
            j -= 1
        drive_servo(18,0)
        drive_servo(13,180)
        time.sleep(10)
    turn_off(13)
    turn_off(18)
    print("end of loop")
if __name__ == '__main__':
    try:
        motion_process = multiprocessing.Process(target=drive_motion)
        motion_process.start()
    except KeyboardInterrupt:
        motion_process.terminate()
```

D. Networking

The RaspberryPi can be connected to a WIFI network in two ways:

i. Accessing the graphic user interface of the RaspberryPi using a monitor, keyboard and mouse. Once on the GUI, simply select the desired WIFI network name and enter the password to connect.

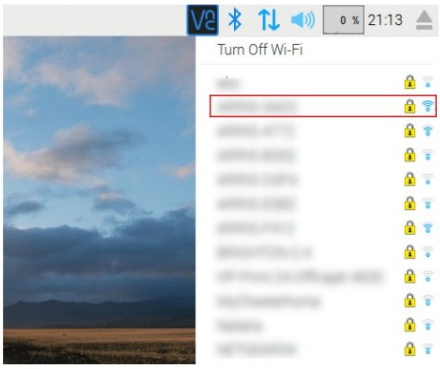

Figure D.1: Connecting RaspberryPi to a WIFI network.

ii. Editing and change the **wpa_supplicant.conf**[6] file configuration. To do this, execute the following commands to generate the list of WIFI networks available, then insert the network configuration name (SSID) and password (PSK) to the wpa_suplicant file. Edit as shown below, save and exit the configuration.

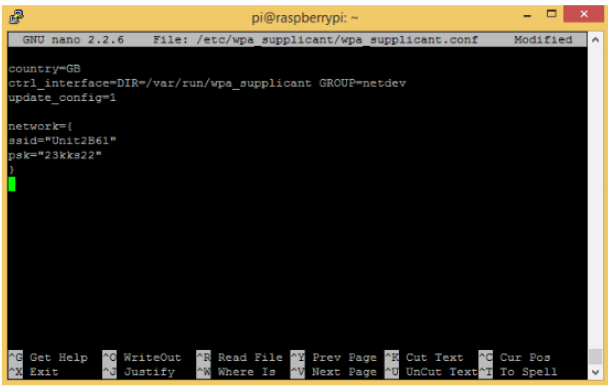

Figure D.2: wpa_supplicant.conf file configuration.

[6]sudo iwlist wlan0 scan
sudo nano /etc/wpa_supplicant/wpa_supplicant.conf
command to start the network sudo ifdown wlan and sudo ifup wlan0.

E. Installation of Raspbian NOOBS on the RaspberryPi

i. Download the Raspbian NOOBS OS file onto a computer.

ii. Insert the SD card into a computer using a card reader and format the SD card.

iii. Copy and paste the NOOBS file onto the SD card drive.

iv. Remove and insert the SD card into the RaspberryPi.

v. Connect RaspberryPi to a monitor, including a keyboard and mouse to view GUI.

vi. Power on the RaspberryPi using the +5V power supply cable.

vii. Follow the on-screen information to install the Raspbian NOOBS OS full desktop version.

viii. Select language (English) and set up the network connectivity (enter the SSID log in details for the WIFI network i.e. username and password).

ix. Set up the log in details (username and password)[7]·1 for the RaspberryPi.

x. Complete the installation and reboot the RaspberryPi.

xi. Access the RaspberryPi graphic user interface.

xii. Run the following commands in terminal window to update RaspberryPi OS package list.

```
cd /home/pi/
sudo apt-get update
sudo apt-get install
```

Figure E.1: Installation of Raspbian NOOBS OS on the RaspberryPi.

The steps above complete the preparation and setup of the RaspberryPi microcontroller.