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Daniel J. Ricks
Brigham Young University - Provo

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Design and Evaluation of a Humanoid Robot for Autism Therapy

Daniel Ricks

A thesis submitted to the faculty of
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Master of Science

Mark B. Colton, Chair
Michael A. Goodrich
Brian D. Jensen

Department of Mechanical Engineering

Brigham Young University

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ABSTRACT

Design and Evaluation of a Humanoid Robot for Autism Therapy

Daniel Ricks

Department of Mechanical Engineering

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Recent evidence has shown that children with autism may behave more pro-socially when interacting with a robot than with a human. The objective of this research is to develop a robotic system for use in the clinical treatment of children with autism. The governing assumption behind this thesis is that using a robot in a clinic, under the guidance of a trained therapist, may lead to therapeutic benefits that may not be achieved without the presence of the robot.

The robot Troy was developed to fulfill such a role in a clinical setting. The primary objective was to design a robot that would be engaging to the children. Secondary objectives included making it versatile, easy to use, and affordable enough for wide-spread use. To facilitate engaging activities for the children, the robot needed to be able to express facial emotions as well as have arms that can move similar to humans. The resulting design is an upper-body humanoid robot with two four-degree-of-freedom arms and a two-degree-of-freedom neck. The face is generated by a small computer monitor mounted on the neck. Troy is connected to a user interface so that its actions can be sequenced and controlled by a clinician during a therapy session.

Although the long-term clinical benefits of using robots like Troy must ultimately be determined by experienced therapists, preliminary clinical trials suggest that Troy is an engaging tool that helps the children become more interactive during therapy sessions. Therapists note that children are intrigued by Troy, and while Troy is present the children have been observed to interact more with the therapists in the room. This gives us further hope that robot-assisted autism therapy will help these children generalize what they learn in the clinic to other aspects of their life.

Keywords: Daniel Ricks, robotics, design, autism, therapy

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1 INTRODUCTION

Robot-assisted autism therapy is a promising new field of research in which robots are used in clinical therapy sessions to help children with autism learn important social skills. This thesis presents 1) the evaluation of related work in the field of assistive robotics, with particular emphasis on work with children with autism; 2) the design and construction of the robot Troy for use by therapists in clinical settings; and 3) collaborative work with therapists to make Troy a useful tool for clinical use with children with autism.

The hypothesis of this research is that a robot that is designed and used properly will prove useful in aiding a clinician to engage a child in therapy. An upper-body humanoid robot named Troy was developed with the goal of helping children with autism to better interact with therapists in the clinic. It is left to the clinicians to determine whether the robot-assisted therapy is more effective than traditional therapy, although initial results suggest that Troy will be effective in helping children to interact more in the clinic.

1.1 Motivation

There is growing anecdotal evidence that robots provide unique opportunities for assisting children with autism. While interacting with robots, children with autism exhibit social behaviors, such as imitation, eye gaze and joint attention, which may be useful in potential treatments [1], [2]. These social behaviors are typically rare in children with autism, but evidence suggests that robots trigger them more often than normal in such children; sometimes these behaviors can be prompted and sometimes they are spontaneous [3].

Autism is a behavioral disorder characterized by (1) deficient social interaction, (2) poor communication skills, and (3) abnormal play patterns, and affects 0.2-0.4% of the general population [4]. Perhaps the most visible manifestation is the difficulty with which children on the autism spectrum interact with their peers. They often avoid eye contact, remain aloof from others, and fail to follow many social norms. They also often fail to recognize the emotional states of others and do not understand that their own actions affect what others do and how they feel. Nearly all children with autism exhibit some level of language impairment, which can range from a complete lack of verbal communication, to prolific talkers who talk incessantly about favorite topics without allowing communication partners to add to the conversation. Most children with autism engage in stereotypical behaviors and repetitive play, such as constantly repeating the same joke or flapping their hands when they are excited. Many fail to use imagination and creativity during play, but some study a single subject tirelessly and learn all there is to know about it. Children with severe autism may exhibit all of these symptoms and appear to live in their own world, whereas higher-functioning children on the autism spectrum may only exhibit mild forms of these attributes [5].

The causes of autism are poorly understood, with only a small minority of cases stemming from a known etiology. The signs of autism, however, may be observed at an early age and remain throughout the person's life.

Myriad treatments have been proposed to ameliorate the effects of autism, some of which have been moderately successful in helping children to manage symptoms, interact with others, and hold jobs as adults [6], [7]. The relatively new field of robot-assisted autism therapy aims to develop novel treatments aimed at improving the quality of life for children with autism and their families.

1.2 Related Work

One of the primary contributions of this graduate research is an extensive literature review on the work others have done in the field of assistive robotics. This is the first time that assistive robotics has been studied at BYU, and so it was important to build a thorough literature review on the subject to inform and give direction and rigor to our research. The following subsections contain some of the key findings of this work, and a more complete literature review, with more than 120 references, was also conducted.

1.2.1 Treatments in Robot-Assisted Autism Therapy

Researchers have investigated the use of robot technology to achieve specific therapeutic objectives for children with autism. In this section we explore the trends in robot-assisted diagnosis, research, and treatment of children with autism. Specific applications are discussed and observations on their effectiveness and lessons learned are presented.

Diagnosis

Early intervention has been shown to greatly increase the long-term benefits of clinical therapy in children with autism [2], and consequently, there is a focus on diagnosing autism at earlier stages in development, which could lead to higher functionality later in life. Therapists are generally unable to diagnose autism until children are about three years old and have missed typical developmental milestones [8].

The use of technology in the early diagnosis of autism has received increased attention in recent years. At Yale, researchers are exploring eye-gaze patterns of infants as a potential diagnostic tool. The method is based on the fact that typically developing children exhibit standard ways of focusing on the movements of others, especially on their caregiver's face and eyes [9], [10]. These gaze patterns develop before typical infants learn to speak, and thus may provide a method for early detection of autism. From an early age, children with autism show a marked difference in their gaze patterns; it has been observed that they concentrate more on their caregiver's mouth than eyes, if they focus on the face at all.

Researchers in Italy are using three specially designed sensors to detect abnormalities in infants which could lead to early autism detection. The first is an eye-gaze tracking device with audio cues to determine if the children respond appropriately to audio and visual prompts. The second is a set of motion-sensing ankle bands and wristbands that can be worn by infants as young as two weeks old. The third is a toy ball with embedded force and tactile sensors that is able to quantify the way in which children handle and play with the ball. These sensors are placed on children in infant centers in order to establish a baseline to which others can be compared [8].

Other groups have taken a similar approach and have had great success using sensors to distinguish between children that do and do not have autism [38], [39]. In the future, the ideal is to use these devices with infants, and an early diagnosis of autism could be reached if abnormalities are detected. A combination of these devices would likely lead to more reliable diagnosis, and early interventions could begin. The children would then need to be monitored as they develop to ensure they are not misdiagnosed.

Another difficulty associated with autism diagnosis is caused by the lack of repeatability during screenings. Since autism is a behavioral disorder, it is diagnosed through an experienced clinician’s evaluation of their interactions with the child. The clinician cannot perfectly repeat the same actions from one evaluation to another, which can cause the children to appear on various levels of the autism spectrum. Although robot repeatability will not help diagnose children at a younger age, it is believed that, by using a robot as standard stimuli in these autism screenings, a more consistent autism diagnosis can be reached [10]. Together, these efforts will hopefully result in a new method for detecting autism more accurately and at earlier stages in life. Autism diagnosis is an interesting area for potential future work, but it will not be further addressed in this thesis.

Self-Initiated Interactions

One component of the impaired social skills of children with autism is a deficit in their ability to initiate social interactions. Many of these children have difficulties requesting things they want or need, and many clinical therapies focus on helping them to be more proactive in their relations with others. For example, when a child is hungry a desirable behavior would be for the child to ask for food, rather than resorting to a tantrum. It is common for a clinician to encourage the child to ask to play with certain toys, and reward them with those toys after the request is made. While it is very useful to help the child appropriately answer questions when asked, it is even better if the child makes the initial request. So it is better if the child requests to play with the blue ball instead of asking them which color ball they would like to play with. In an effort to promote this self-initiated interaction, researchers are extending this idea to using robots to encourage the child to engage the robot proactively.

At USC, researchers built a small, mobile robot that is appealing to children with autism. The robot has a large button on its back that the child can push, to which the robot responds by blowing bubbles [11]. This encourages the child to engage the robot proactively (by pushing the button) in order to receive the desired reward (the bubbles).

The University of Hertfordshire's AuRoRA Project has sought to take advantage of child-initiated behavior. As they have performed studies involving interactions between children with autism and their robots, the clinicians have intentionally played a passive role. Using this approach, there have been occurrences during the children's interactions with the robot in which the children have initiated communication with the therapist in much the same way as would be observed with a typical child [12].

Turn-Taking Activities

Other researchers have focused on using robots to help children with autism participate in turn-taking behaviors. Due to a lack of turn-taking abilities, these children often have difficulties conversing with others, and may be found rambling without allowing their conversation partner to participate. At the University of Hertfordshire and the University of Southern California, researchers have built small mobile robots that react to the children that play with them. The goal is for the children to become accustomed to waiting for responses after they say or do something. The Hertfordshire mobile robot, Labo-1, for example, can play games of tag with the children, which forces them to alternate between engaging and avoiding the robot [13].

Imitation

Another common technique used in clinical sessions is imitation therapy. Therapists have found that when an adult "imitates the child's behavior, the child displays more social responsiveness, for example, increased eye contact, touching, vocalizing, and toy exploration" [6]. The children often lack the ability to recognize their peers and caregivers as "social others," and imitation activities may help the children to realize that their actions are related to the actions of those around them. Imitation may help them to see that their actions are observed by others who may, of their own accord, repeat those actions, and that the child can also repeat the actions that are initiated by others. Imitation also helps improve hand-eye coordination, and, according to P. Hinerman, "Imitation training is the first step in teaching autistic children to communicate….Children who can be taught to imitate motor responses are more likely to learn to use some form of communication…. Start with large muscle groups, like raising an arm, and then move down to more subtle ones like a smile or frown" [14].

Most researchers that have built robots to help children with autism have attempted some form of imitation therapy. At the University College London, children with autism attempted to imitate another person's hand as well as a simple robotic hand. The children appeared to imitate the human hand only slightly better, which establishes robot-based imitation as a plausible therapy [15]. In another study some children, with and without autism, were asked to imitate a reach and grasp motion performed by a robot and by a human. They observed that the children with autism actually reacted faster to the robot imitation than they did to human imitation, while the opposite is true for their typically developing peers [16].

Researchers at the University of Sherbrooke compared the children's ability to imitate their robot Tito against their ability to imitate another child [17]. They found that the children with autism would stand closer to the robot and look at it more during the interaction than they would when imitating another child. The child was better able to imitate their peer than the robot, but that may have been due to the limited motion capabilities of the robot.

Likewise, researchers in the AuRoRA project at the University of Hertfordshire used a doll-like robot, Robota, in reciprocal imitation activities where the child would imitate the simple movements of the robot and vice versa. Since their robot's automatic imitation software required the child to sit still and use a limited range of motions, they performed their studies by having the robot's imitative motions controlled remotely by a therapist [12]. Therapist-controlled imitation is also used in interactions with robots such as Keepon and FACE [18], and it has been shown to generate novel interactions directly between the child and the therapist. At the University of Pisa, the FACE robot has been used to imitate children's facial expressions instead of general arm and body movements like with Robota and Tito. They observed that the children generally imitate the expressions on FACE better than on other humans [19], and they are working to automate this process so that a therapist will no longer have to control the imitative expressions.

Emotion Recognition

Studies have shown that children with autism generally have difficulties reading facial expressions, and some researchers are attempting to help alleviate this deficiency [20]. The human face is very complex, and facial expressions of emotions carry subtle nuances that are difficult for these children to understand. The amount of information contained in the human face can cause children with autism to feel overwhelmed when looking at someone else's face, and making eye contact can result in sensory overload. There are also slight differences in expressions between people, which are hard for many children with autism to understand. The same person could even smile twice, in somewhat different ways, and to a child on the autism spectrum they could appear to be two entirely different expressions. Robots are more repeatable than humans, and so they may prove to be better able to teach children with autism about facial expressions.

At the University of Hertfordshire, the robot KASPAR can represent facial expressions with less complexity than a real human face [21]. This potentially helps children with autism focus on KASPAR's face without showing the anxiety and sensory overload they often experience around humans.

Researchers at the University of Sherbrooke performed a study to evaluate how well children with autism are able to recognize and imitate, among other things, the facial emotions of a human mediator and their robot Tito, which has a mouth made up of small LEDs that can represent a smile or a frown. Four low-functioning children with autism were selected to participate in their study; two were paired with Tito, and the other two were paired with a human mediator. During a series of 22 sessions, the children were each asked to imitate the facial expressions of their mediator, and it was observed that the children paired with the robot were better able to imitate the facial expressions than those children paired with the human mediator [17].

The FACE robot at the University of Pisa is designed to closely approximate a real human face and show the detail of human expressions while still remaining repeatable. In studies with FACE, children with autism were asked to select pictures of people making the same expression as the robot as well as verbally naming each expression made. They also gave the child a scenario and asked them to pick an appropriate emotional expression for FACE to make [22]. These therapies are aimed at helping the children to generalize the information they learn in the therapy session to other situations. After performing these tasks over a series of therapy sessions, the children were tested using the Childhood Autism Rating Scale (CARS), and it was shown that, while working with the robot, all four of the children improved in the categories of Emotional Responses and Relating to People [19].

Joint Attention

Another deficiency that children with autism often have is the ability to consciously focus on the same object as another person. It is often hard to remain focused on specific things, and so helping them attend to specific items is critical to their success in learning. Joint attention occurs when the child and someone else are both able to attend to the same object or activity. These children frequently do not acknowledge others around them, and joint attention activities can help them to understand that others are aware of them, that they are aware of others, and that they are both aware of the same object.

Multiple research groups have focused on joint attention in their clinical studies, but they have used it in very different ways. With the robot Keepon, operators remotely direct its gaze toward the child or toward an object to establish joint attention [18]. As it alternated between establishing eye contact and looking at an object, Keepon would emotionally react whenever the child made any significant social interaction. When the child would look or point at the same object that Keepon focused on, Keepon would bounce and rock to show its excitement, thus encouraging the child to interact even more. The Toyota Technological Institute, along with researchers from the Aizu and Aoyama Gakuin Universities, also used a robot to encourage, and then autonomously detect, joint attention with a child on the autism spectrum [23].

Researchers at the University of Hertfordshire and the University of Sherbrooke have used joint attention as a metric to see how receptive children are to their robot [17], [24]. They found that children with autism in their studies are generally more willing to interact with and pay attention to robots than they are with other people. They also observed children with autism interacting with their robots, showing concern for them, and focusing on them in the same ways that their typically developing peers would. While some of these interactions are merely anecdotal, the consistency of such interactions makes joint attention activities a promising part of robot-assisted therapy [1].

Triadic Interactions

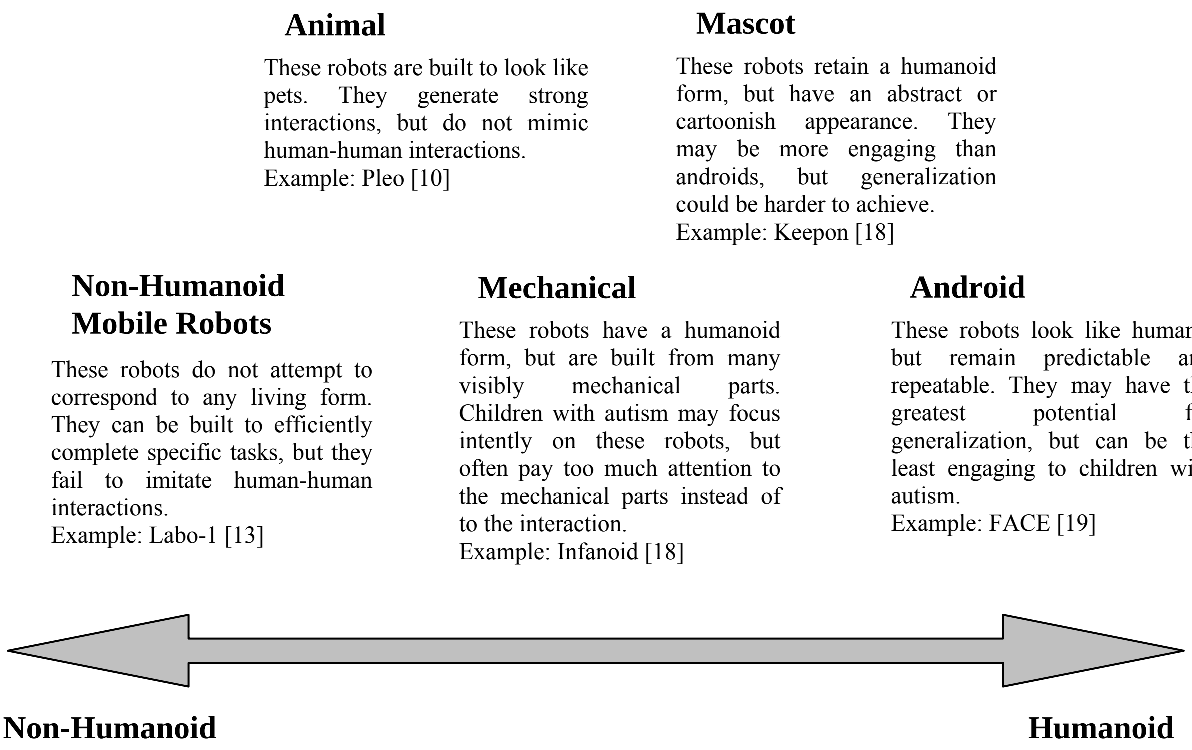
Since mechanical objects like toys and robots are simple and predictable, they can be very appealing to children with autism. Many novel social interactions have also been observed while the children have been playing with these robots. The goal, however, is not and should not be to improve the way that they play with toys or interact with robots. The goal, rather, is to use these objects to improve their interactions with other people. In an effort to help these children generalize what they learn with the robot to interactions with their peers and caregivers, multiple researchers have begun to focus on triadic relationships. A triadic relationship is one that consists of the child, the robot, and another companion, which may be another child, a parent, a teacher, or a clinician. The importance of this form of interaction, known as robot-mediated interaction [25], has been noted by at least four researchers [10], [17], [26], [27].

The various forms of triadic interactions take advantage of the robot as a social "pivot," where the robot helps to elicit interactions between the child and other humans. During clinical sessions with their robot Keepon, Kozima *et al.* observed children with autism using Keepon as a social pivot, resulting in increased interaction with their peers, parents, and therapists. In one case study, a three-year-old child with autism avoided playing with Keepon until after observing another child playing with it. The child with autism then imitated the other child by repeating their actions towards Keepon. That same child later made referential looks at her mother and therapist during the time she played with Keepon [26]. These types of actions are not typical for children with autism, but there was something about the presence of the robot that helped elicit them.

In two independent studies [17], [27], researchers found that as children realized that the therapist was controlling the robot, new excited interactions between the child and experimenter emerged. In a study by Robins and Dautenhahn, a child took the experimenter by the hand and led him to the robot to play with the robot as well. At one point, when the child noticed that the robot leg was broken, the child tried to convey that information to the experimenter. Through this triadic interaction, the child exhibited self-initiated behavior and joint attention with their experimenter. On another occasion, while imitating the robot Robota, the child realized that the experimenter was actually controlling the motions of the robot. When the experimenter made mistakes in the imitation game, the child looked at the experimenter, laughed, and corrected him [27]. Since there appears to be a benefit to having the experimenter in the room controlling the robot in real time, at least two researchers have developed tools that allow their clinicians to do so [3], [10]. It has been hypothesized that triadic interactions are key to achieving generalization [3], meaning that the positive social behaviors will occur outside of the clinic or laboratory.

1.2.2 Design of Robots for Autism Research and Treatment

Much consideration has been given to the type and form of robots used in autism research. Some robots used for this purpose are humanoids, while others are small, mobile, and carlike. Some attempt to achieve a realistic human appearance, while others have created robots with very mechanical forms, and still others have created robots with a cartoonish, or mascot-type form [21]. A study was also performed to evaluate if a robotic avatar would be sufficient to elicit the types of reactions that have been observed with other robots. Figure 1 shows a comparison of the types of robots used in autism therapy based on their location on the humanoid to non-humanoid spectrum. Each of these types of robots has its benefits and drawbacks in working with children with autism.



Animal

These robots are built to look like pets. They generate strong interactions, but do not mimic human-human interactions.
Example: Pleo [10]

Mascot

These robots retain a humanoid form, but have an abstract or cartoonish appearance. They may be more engaging than androids, but generalization could be harder to achieve.
Example: Keepon [18]

Non-Humanoid Mobile Robots

These robots do not attempt to correspond to any living form. They can be built to efficiently complete specific tasks, but they fail to imitate human-human interactions.
Example: Labo-1 [13]

Mechanical

These robots have a humanoid form, but are built from many visibly mechanical parts. Children with autism may focus intently on these robots, but often pay too much attention to the mechanical parts instead of to the interaction.
Example: Infanoid [18]

Android

These robots look like humans, but remain predictable and repeatable. They may have the greatest potential for generalization, but can be the least engaging to children with autism.
Example: FACE [19]

Figure 1: Robot Types Used in Autism Research

Avatars

A simple trial was performed here at BYU, in conjunction with the Honda Research Institute, to evaluate if a robotic avatar is sufficient to elicit significant social interaction with children with autism. Two children with autism were brought into a room where an avatar of the Honda robot Asimo was projected onto the wall. Although the children were directed to pay attention to the avatar, it did not appear that they even acknowledged its presence. On the other hand, some have used videos and cartoons to teach children with autism subjects such as emotion recognition with some success [28]. In another study, two children with autism wore a virtual reality helmet to simulate a real situation [29], and in this study one of the children recognized that he was in a 3D world while the other still interpreted the world as being 2D. This suggests that using a virtual medium with children on the autism spectrum may have mixed reactions. For typically developing adults, preliminary studies in [30] suggest that physical embodiment is preferred over virtual interactions. Consequently, we believe that a physically embodied robot should encourage more interest and interaction than a virtual avatar.

Non-Humanoids

Non-humanoid robots have been used by various researchers because of their simplicity and the ease of creating interesting and engaging interactions. By leaving aside the human form, researchers have been able to create simple robots that are not limited in appearance, but rather are able to have whatever form is best suited for their applications. The bubble-blowing robot at USC, for example, was able to be built much simpler by not forcing it to take on a human form [11]. University of Hertfordshire researchers also used a non-humanoid robot, Labo-1, that can play games of tag with the children [13], and, at Yale, studies are being performed using a mobile, robotic dinosaur named Pleo that can convey desires and emotions through recorded sounds and body language [10]. Pleo's expressiveness, versatility, and pet-like appearance help to engage the children in the clinic. As a child with autism sees something with a human form, they may become withdrawn and avoid interactions. Robots in the forms of animals, cars and toys often do not trigger these same reactions, which can make them more engaging than robots with a humanoid form. In addition to helping the children engage in activities, non-humanoid robots can often be much simpler and affordable.

Humanoids

The benefit of using humanoid robots in autism therapy research is that there may be a greater potential for generalization. For example, a human form allows children to engage in imitation and emotion recognition activities. Although some general guidelines on robot designs have been proposed, there is no clear consensus as to what a robot used in autism research should look like.

Robins *et al.* performed a study to evaluate the importance of the robot's appearance for children with autism. The children were asked to interact with the doll-like robot Robota when it was dressed as a doll and while it was dressed in plain white clothes with a covering over its head. Other children were asked to likewise interact with a man disguised as a robot and later with that same man dressed in typical business attire. In both instances, the children appeared to be more interested in interacting with the less human of the two. From this study, they concluded that robots that interact with children with autism should avoid the details and complexity of a human while still holding to the humanoid form. They subsequently designed the robot KASPAR to fit these design criteria [24].

Researchers at the National Institute of Information and Communications Technology in Japan came to similar conclusions based on their work with the robot Infanoid. They noticed that as children with autism interacted with Infanoid, they tended to pay more attention to the mechanical parts of the robot's body than to the interaction they were trying to achieve. This observation appears to be consistent with general beliefs regarding children with autism, i.e., that they gravitate toward simple, repeatable, mechanical objects. The small, soft, snowman-shaped robot Keepon was designed to minimize any distractions the children may have, but it still appears roughly humanoid, with a head, body, eyes, and nose. Since it cannot show facial expressions, emotions are effectively conveyed by shaking, rocking, and bobbing up and down [18], [26]. Other researchers have followed a similar approach by building simplistic, mobile, humanoid, robotic platforms that have likewise been successful in interacting with children with autism [11], [17].

Most researchers tend to advocate the notion that simpler is better because it appears to be more engaging to the children. The researchers at the University of Pisa have taken a different approach by creating the robot FACE, which was designed to appear as realistic as possible. FACE utilizes a skin that can accurately display human emotions and complexity while remaining more repeatable than a real person [19], [22].

When designing an android type robot, many researchers feel that it is important to avoid what is known as the "uncanny valley" [31]. The uncanny valley stems from the notion that people like the appearance of a robot as it becomes increasingly more human, but there comes a point when the robot becomes "creepy." Figure 2 shows a diagram of the level of emotional response compared with the level of anthropomorphism in the robot. While in the uncanny valley a robot looks like a human, but misses subtle nuances inherent in a human face, which gives it a disturbing feel as if it were a moving corpse. Along with this notion of the uncanny valley are the unfulfilled expectations associated with an overly humanoid robot. If the robots look human, users naturally expect them to act human, and when they act robotic, it can perturb the user. The effects of the uncanny valley on children with autism are not well understood. Reports on humanoid robots such as FACE and KASPAR suggest that the children enjoy interacting with these robots, and typical reactions associated with the uncanny valley have not been noted [22], [32]. This may indicate that the robots have missed the uncanny valley or that children with autism are not affected by this phenomenon. If the latter is the case, then a robot that would typically land in the uncanny valley would not be detrimental for work with children on the autism spectrum.

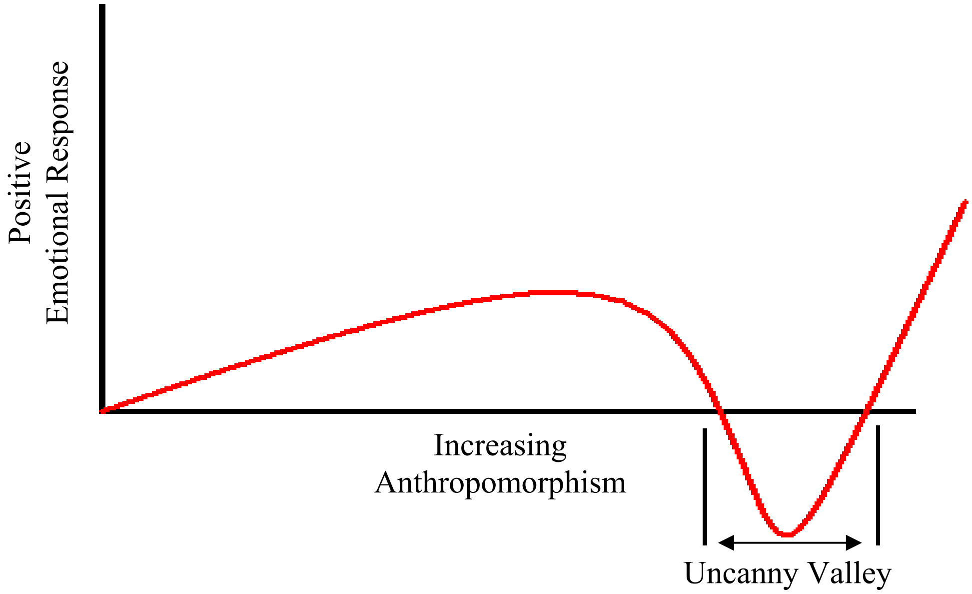


Figure 2: The Uncanny Valley [31]

Simple robots may be more engaging to children with autism, but they arguably have less potential for crossover or generalization due to the large divide between their appearance and the appearance of another person. Consequently, each type of robot design is suited for specific types of interactions, and the robot should be designed with specific therapeutic goals in mind.

1.3 Trends and Future Directions

Based on the work of many skilled researchers, it is clear that robot-based therapies have potential to help in the treatment of children with autism. The potential for earlier and more repeatable diagnosis, and the social skills these children demonstrate while interacting with robots are very compelling and warrant further work to investigate the best ways to utilize robots in this field.

Unfortunately, significant generalization of the skills learned in these therapy sessions has not been observed outside of the clinic or laboratory. Researchers have noted that, after extended exposure to the robots, the children have become more sociable with the robots themselves while little has been said about how well the kids can apply these skills outside the clinic. For this reason, we feel that, by making the clinical experience as similar to the outside world as possible, we can focus on the end goal of increased social interaction outside of the clinic. Consequently, we feel that, coupled with the aforementioned therapies, triadic interactions have the greatest potential for success. Since robots may never achieve the types of rich social interaction that human-to-human interactions provide, using the robot as a tool to increase interaction with the therapist or other humans may prove to be very productive.

A further possibility is to bring the robot out of the clinic as a "cognitive orthotic" [3]. If the mere presence of the robot allows the child to be more social, a portable robot that the child could have on hand may have the potential of helping the child open up to peers and family members. Using a robot in the clinic has opened up communication between the child and the therapist, and this same phenomenon may prove to be beneficial in the home and school as well. These cognitive orthotics will not be treated in this thesis, but are the subject of potential future research.

The appearance of the robot may have a great influence on the clinical benefits achievable with a given robot. If simple interaction is the objective of a given treatment, then a non-humanoid may be the best option; however, humanoids may be better for simulating human-to-human interactions. Initially, children with autism tend to be more interested in working with simplified, abstract forms rather than realistic depictions of another person, and these types of robots will help to engage the child especially when they are first introduced to the robot. Realistic robots have the benefit of being similar to humans and so there is a possibility (unproved at this point) that generalization may be more easily achieved. As a downside, realistic robots may initially be less appealing to children with autism.

Consequently, multiple researchers have proposed that a series of robots, or a robot with a changeable face, be developed to take advantage of the benefits of each of these types of robots [10], [24]. The robot Barthoc was built to have interchangeable skins which cover the mechanical structure of the head [33]. For example, the head could appear to be male or female depending on user preference. Barthoc is not currently used with children on the autistic spectrum, yet its designers also realized that a robot that could change its appearance would be beneficial. Children could begin therapy with a simplistic robot and, as they become comfortable with that one, a more realistic robot could be introduced. In this manner, the child could be weaned off the robot-mediated interactions and become more comfortable interacting with others.

1.4 Approach and Contributions

Our objective was to create a robot that will be a useful tool to assist clinicians in engaging children with autism in meaningful interactions in clinical therapies. The robot is principally to be used to form a triadic interaction between the child, clinician, and robot using protocols such as imitation and turn taking behaviors. It is believed that through better interactions with other humans, children with autism may develop the skills they need, and the robot's presence in the clinic is meant to enhance those interactions. To help facilitate better interactions, the robot's arms and neck should allow it to look and point in any direction so that it is versatile and has human-like motion. This versatility allows the robot to have a greater repertoire of useful activities that therapists can use during a session. It should also be equipped with a digital face so that its appearance can be easily changed according to the specific goals the clinician may have for a particular child. It should also contain a speaker so that it can have verbal communication capabilities. The robot will initially be used in the BYU Comprehensive Clinic where trained clinicians can evaluate the effectiveness of robot-assisted autism therapy.

This research has led to a number of significant contributions in robot-assisted autism therapy at BYU. First, a thorough literature review on the subject of robot-assisted autism therapy has been compiled and is available for the use of researchers, clinicians, and professors. The position paper, "Toward Therapist-in-the-Loop Assistive Robotics for Children with Autism and Specific Language Impairment," was published in the 2009 *Artificial Intelligence and Simulation of Behavior (AISB) New Frontiers in Human-Robot Interaction Symposium* in Edinburgh, Scotland [3]. The paper includes some of the findings of this literature review, and outlines some of the preliminary directions and objectives of our research. The survey paper, "Trends and Considerations in Robot-Assisted Autism Therapy," summarizes, in greater detail, many of the findings of the literature review, and has been accepted for publication in the 2010 *IEEE International Conference on Robotics and Automation* (ICRA) [41].

The most important contribution of this work was the design and construction of a robot for use by therapists in clinical settings. The robot Troy was designed and built to achieve the aforementioned objective. Initial experiments indicate that the robot meets its technical objectives; additional experiments are underway to develop clinical activities and evaluate the robot's clinical effectiveness. Control software was created and a collection of actions made available to create smooth robot motions and to enable clinicians to use it in an effective manner. An additional conference paper addressing the robots, user interface, and objectives of this research, titled "Detailed Requirements for Robots in Autism Therapy," has been submitted to the *IEEE International Conference on Systems, Man, and Cybernetics* [42], and a paper addressing the design of the robot Troy will soon be written for an upcoming conference. The robot hardware and software were also tested to assess their usefulness and reliability, and trials have been performed in a clinic to evaluate the robot's effectiveness in helping children with disabilities. The results of these trials have been encouraging. Long-term trials are underway to evaluate the clinical benefits of robot-assisted autism therapy.

2 ROBOT DESIGN

2.1 Troy

The robot Troy was designed to be used in a clinic to help children with autism become more engaged in their therapy sessions. It was designed to imitate human arm and neck motion and show human facial expressions. The arms are used for simple interaction activities such as pushing a toy car and waving hello, and the face can express simple human emotions. It was developed to be placed in the BYU Comprehensive Clinic where it can interact with clinicians and children. Since it was neither designed to be mobile nor handled by the children, Troy is an upper-body robot that may be placed on the ground or on a table while the therapists control its interactions. The following sections detail the design and testing of Troy.

2.2 Body and Arms

Troy is an upper-body, humanoid robot that was designed to be roughly the size of a four year old child. It is 25” tall, and has two 12” long arms, whereas an average four year old is 24.9” tall from the crown of the head to mid-thigh and has 11.4” long arms from the shoulder to the wrist [34]. Many children begin treatments for autism when they are around three to four years old, and the robot was made to be their same size. This situates the face at the child’s eye level when both are seated on the ground, which is a natural position for interactions. It was also feared that a robot larger than the children could be intimidating, and a robot that is too small would lack the ability to show naturalistic humanoid emotions and movements.

The arms have 4 degrees of freedom (DOF) each, including 2 DOF in the shoulder for flexion/extension and abduction/adduction. The remaining 2 DOF are for humeral rotation and elbow flexion/extension. These 4 DOF enable each robot arm to point in any direction and have a range of motion similar to that of a human arm. The joints were also designed to minimize the pinch points and make it as safe as possible. In consultation with participating clinicians, it was determined that wrists and hands were not necessary to achieve the levels of interaction used in the clinic, and the added size, weight, and complexity of the motors needed to actuate the wrists and hands would mean that the arms and motors would need to be much larger and stronger to support them. It was felt that the increase in size and cost was not worth the benefit of having the hands. Instead, clinicians placed strips of hook and loop fasteners on the ends of the arms to hold small objects such as a small xylophone mallet. Various views of Troy are shown in Figures 3-5.

Figure 3: Troy Front View

Figure 4: Troy Side View

Figure 5: Troy Back View

Troy weighs 15 lbs and sits on a 9” x 11” base. The base is large enough and the robot heavy enough to hold it in place without tipping over if it is lightly pushed, yet it is light enough to easily be moved around by a therapist and not do much damage if it does tip over.

A speaker was also placed within the body of the robot and connects to the computer through a USB port. Sound may either be played through the built-in speakers on the computer, or for computers that connect with the external speakers, the sound may be played through the robot’s body. The current laptop in the clinic does not have the appropriate drivers to connect with these speakers, and so the laptop’s built in speakers have been used; up to this point the children appear to not notice the difference in sound origin from the robot to the computer.

2.3 Neck and Head

Since the generalization of learned skills is difficult to achieve, Troy was designed with a neck and head that allow researchers and therapists to investigate different types of faces. The head is easily detachable if therapists find it desirable to change the appearance or function of the head, and the current face is realized with a small LCD monitor.

Since children with autism tend to prefer less realistic robots at first, Troy was designed to initially have a cartoonish, simplistic face so that the children will not be intimidated or distracted by faces with greater realism or complexity. Troy was also designed to allow researchers to change the face to a more realistic or complex form after the child becomes accustomed to the original. This could also lead to useful emotion recognition therapies. It would ideally make these child-robot interactions more similar to child-human interactions, which could aid in transferring their skills out of the clinic. Naturalistic approaches to autism therapy teach that the more the clinical activities reflect the world outside of the clinic, the easier it is for these skills to come into effect outside the clinic [40]. Thus, a robot with a realistic face could help in the generalization process, and by slowly progressing to the image of a real human face, the robot could have the best of both worlds.

Troy was designed to have a computer screen for a face instead of a single mechanical face. This allows for the face to be easily changed without having to change the actual hardware. The screen is a 7” Mimo-730 display with 800 x 600 pixel resolution, which is mounted inside a plastic head structure. This plastic structure makes the head appear to have a physical embodiment, rather than simply a computer screen. It gives it a more humanoid feel and moves the head away from being a simple avatar on the screen and into an embodied face and head structure. As suggested in [35], the head is typically mounted horizontally (landscape), which helps prevent giving unrealistic expectations to the user and avoids the uncanny valley. The head can easily be mounted vertically (portrait) to have more humanoid proportions when greater realism is desired.

The face was originally developed to be able to show a neutral face along with the six basic Ekman faces of happiness, sadness, fear, surprise, anger, and disgust [36]. Paul Ekman found that these simple faces are understood worldwide and are not subject to cultural differences. In therapies where a simple positive, neutral, or negative emotion are wanted, the happy, neutral, and sad faces are used as shown in Figure 6. Figure 7 contains the other Ekman faces of fear, anger, disgust, and surprise. The face was initially developed in C++ using the graphical user interface (GUI) creator QT. In this GUI the user is able to select an emotion as well as how subtle or strong that emotion should be. Troy’s controller, on the other hand, is written in C# instead of C++, and it was also undesirable to have a separate GUI run the display. Consequently, the original face program is not currently used, but an animation of simple images based off the original was incorporated into the current GUI in order to consolidate the programs. The conversion was performed with the help of Alan Atherton and Sukhbat Tumur-Ochir, research assistants in the Department of Computer Science.

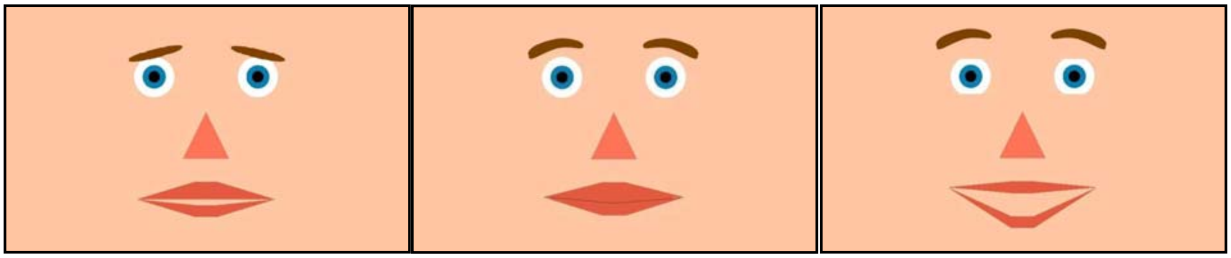


Figure 6: Basic Emotions, Sad, Neutral, and Happy

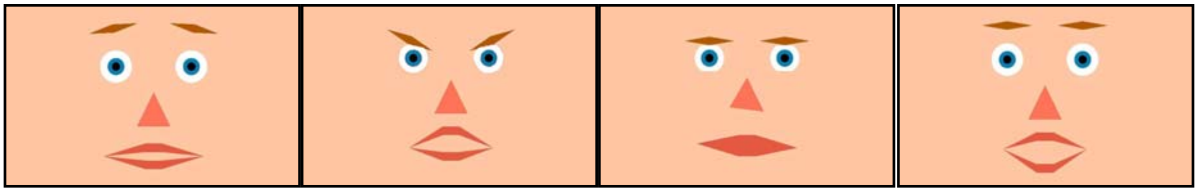


Figure 7: Emotions of Fear, Anger, Disgust, and Surprise

2.4 RC Servo Motors

Actuation for the robot arms and neck is provided by RC servo motors, which were chosen for their compact size, low cost, and ease of use. These motors have an internal feedback loop and a gearbox built into them, which generally make them more compact and affordable than traditional DC motors with a gearbox and encoder attached. These motors are commanded by sending a voltage for a specified time, or pulse width (PW), which corresponds to a specific shaft angle. The motor controller sends a pulse to the servo roughly every 0.02 seconds, and the length of time that the voltage is held determines the angle to which the motor rotates. Within the servo casing, the motor has a potentiometer that senses the current position, and the internal feedback loop moves the shaft to the desired location. Consequently, by simply mapping desired angles into their associated pulse widths, these motors can move to the desired angular positions with ease.

Unfortunately, the ease of use of an RC servo can also be its biggest drawback. The internal feedback and position values are not available to the user, which prevents the user from using an external controller to enforce position tracking. Instead, the position control is achieved solely through the internal feedback in the RC servos. While this limits the type of control methods that can be applied, the internal feedback is still quite good and was deemed acceptable for this project. The other disadvantage of these motors is they have a limited range of motion. They can typically only rotate about 190°, and so careful motor placement was important for the robot to function properly. In order to accommodate for these motor limitations, Troy's arm movements are restricted to actions in front and to the side of its body, and it is not able to reach behind itself.

The servos are driven by a servo controller, which receives commands from a computer via a serial connection. The controller is a Lynxmotion™ SSC-32 Ver 2.01 controller, which was selected for its ability to perform both position and velocity control, as well as send commands to multiple servos simultaneously. The controller has slots for 32 servos, which is more than enough to control the 10 servos used in Troy. All of the motors purchased are made by HiTec™, an industry leader in RC servos, and all of them, except those in the neck, are mounted to the arm and body structure designed specifically for Troy. The motors in the neck are mounted in a pan-tilt mechanism from ServoCity.com. Figures 8 and 9 show diagrams of where the servos are located and what their rotational directions are; Table 1 lists the motor specifications for each joint.

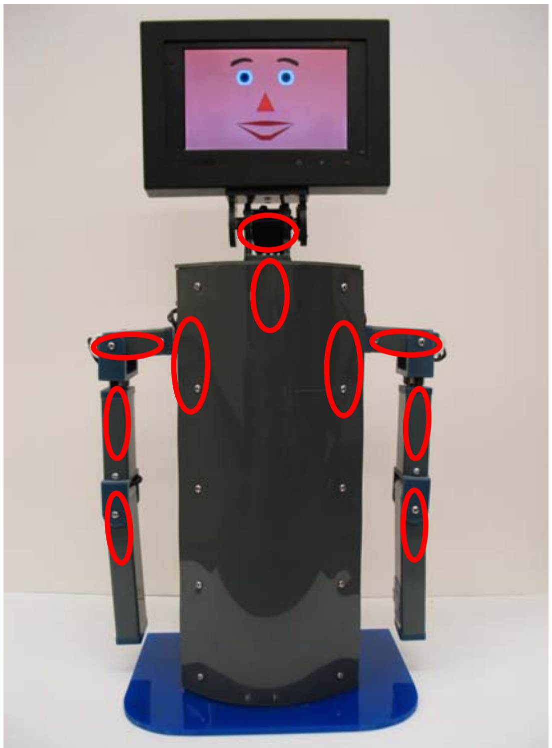


Figure 8: Motor Locations

Figure 9: Motor Directions of Rotation

Table 1: Motor Selection

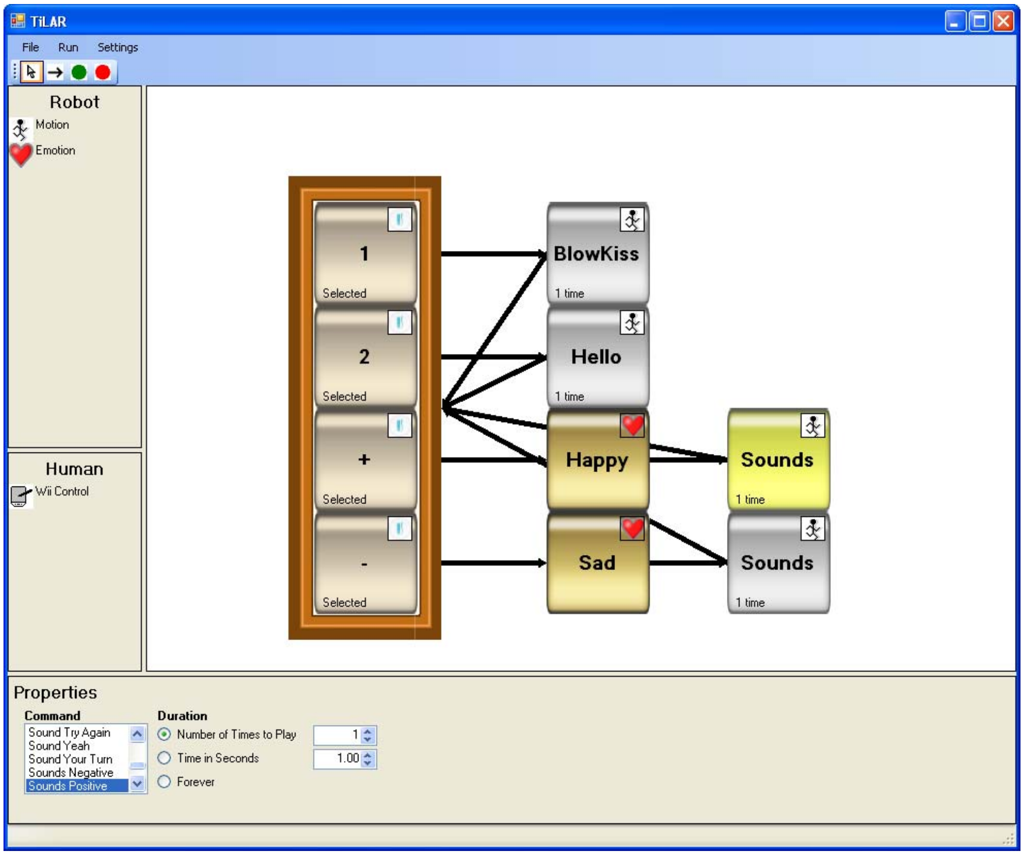
Joint Motion	Servo Number	Servo Size	Servo Torque at 6.0V
Neck	HSR-5980SG	1.57” x 0.78” x 1.45”	333.29 oz-in
Shoulder: Flexion/Extension	HS-805BB	2.59” x 1.18” x 2.26”	343.01 oz-in
Shoulder: Adduction/Abduction	HSR-5990TG	1.57” x 0.78” x 1.45”	333.29 oz-in
Humeral Rotation	HS-985MG	1.57” x 0.78” x 1.45”	172.00 oz-in
Elbow Bending	HS-985MG	1.57” x 0.78” x 1.45”	172.00 oz-in

Motor selections were made based on geometry and torque considerations, both of which were established before constructing the arms using 3D CAD models. The arms were modeled using CAD software NX; drawings of the arm components are included in Appendix A. The distance from the motor shaft to the center of mass for the arm, along with an estimated arm weight, were used to calculate the required static torque output of the motors to support the weight of the arms. Motors were selected that had torque capabilities that exceeded the static torque requirements by a large safety factor to ensure that they were capable of generating arm motions. The motors were later tested by mounting them to a servo horn which had a load greater than the estimated arm weight positioned at the estimated center of gravity. The motors were able to repeatedly handle this conservative estimate of the applied loads, and so they were deemed acceptable for providing the robot motion.

2.5 Robot Actions

For clinicians to use Troy effectively, they must be able to control it. As discussed in [37], users without a technical background need to be able to program the robot to suit their needs. In our case, the end users are clinicians, who must be able to control the robot’s actions to achieve desired therapeutic benefits. This involves creating robot behaviors in advance and executing them in real time.

Researchers in the Department of Computer Science at BYU are developing a GUI that provides a simple visual programming environment to control the robot. The GUI incorporates a finite state machine in which the user can choreograph a series of predefined actions for the robot to carry out. The sequence of actions can be dragged and dropped into the main window, and arrows can be easily drawn between the motion blocks to establish the desired sequence of events (see Figure 10 for an example of the GUI). Along with the set of robot actions, sounds and facial emotions are also available for the user to incorporate.



Properties

Command
Sound Try Again
Sound Yeah
Sound Your Turn
Sounds Negative
Sounds Positive

Duration
● Number of Times to Play 1
○ Time in Seconds 1.00
○ Forever

Figure 10: Example of GUI

To give further control to the clinicians, a Wii™ remote was connected to the GUI. Wii™ remote objects can be placed in the routine, and at these points the program waits for input from the remote before proceeding. These nodes can be joined together to provide multiple options for the clinician to use. For example in Figure 10 the (1), (2), (+), and (-) buttons trigger different action sequences and are all available at the same time. Also, since the remote is connected to the computer via Bluetooth, the therapist can discreetly control the robot without having contact with the computer. It is shown in [27] that, as the child recognizes that the therapist is controlling the robot, the attention of the child could shift from the robot to the clinician. In some situations this could be beneficial, whereas in other situations they may fixate and perseverate on the remote instead of on the therapy, which would be distracting. Therapists have the freedom to emphasize or deemphasize their role in controlling the robot.

Users may currently select from more than 30 pre-programmed actions, 20 sounds, and 7 emotions while programming the finite state machine. The actions are designed to allow clinicians to construct activities that they feel are useful for a given child. When a new therapy protocol is developed, the specific actions required to complete the protocol are programmed and made available for the therapists to use. Some examples of actions include waving hello (Figure 11), moving an arm out to push an object in front of it (Figure 12), and blowing a kiss (Figure 13). After these actions are programmed they are ready to be sequenced and choreographed into therapy protocols which can be combined with various sounds and facial expressions.

Figure 11: Troy Waving Hello Action

Figure 12: Troy Pushing Object Action

Figure 13: Troy Blowing a Kiss Action

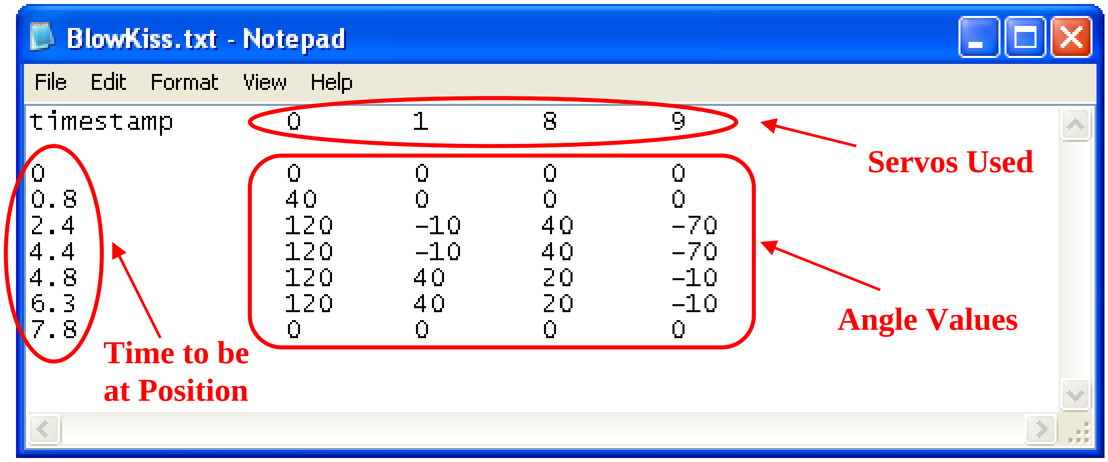
Sounds include simple phrases such as “Hello” and “Your turn,” as well as sounds with positive or negative affect, or emotion, such as “Yeah,” “Good Job,” or “Oops,” and “Oh No.” Positive and negative sound boxes are available for selection in the GUI so that one action button will randomly play a different positive or negative sound. This allows the clinician to push a single button to get various positive or negative sounds instead of the robot saying the same phrase each time.

As mentioned previously, the available facial emotions include a neutral face along with happiness, sadness, surprise, anger, disgust, and fear. For activities where only basic emotions are needed, the face will remain sad, neutral, or happy (see Figure 6); however, for more advanced emotion recognition activities these other basic emotions can also be used (see Figure 7).

Together, these sound, emotion, and action motilities provide a rich repertoire of interaction levels for Troy to use. The clinicians are able to access, choreograph, and play these actions as part of their therapy protocols in ways that will best help with the children with whom they work.

2.6 Software and Control

To control the motion of Troy, the GUI program has a specific class that translates the actions the user specifies into motor commands. When the user sends a command for Troy to perform a motion, the program first looks up the action file associated with that motion. These action files contain a list of which servos will be activated, at what time they should be at each position, and what angle each servo should reach at that specified time. Figure 14 is an example of the action file BlowKiss.txt.



```
timestamp    0     1     8     9

0            0     0     0     0
0.8          40    0     0     0
2.4          120   -10   40    -70
4.4          120   -10   40    -70
4.8          120   40    20    -10
6.3          120   40    20    -10
7.8          0     0     0     0
```

Servos Used

Angle Values

Time to be at Position

Figure 14: BlowKiss.txt Action File

The controller then maps each of these angles into the associated PW for the given servo. These values were found experimentally, and every angle within the servo's range is mapped to a given pulse width.

Sending simple position commands to the servos makes them snap to their new positions as fast as possible, which makes the motions very jerky. To smooth out the actions, a velocity controller is used instead of a position controller. The velocity controller functions by sending an angular velocity command and a rotational direction instead of a position. The motor is sent the angular velocity that will rotate the shaft to the desired position in the given amount of time. For example, if Servo 1 needs to rotate clockwise 20º in 1 second, a command is sent to Servo 1 to move in the clockwise direction at 20º/sec. In terms of pulse widths, the motor speed is

$$S = \frac{|\,\mathrm{PW}_{\mathrm{new}} - \mathrm{PW}_{\mathrm{old}}\,|}{\Delta \mathrm{t}}. \qquad (2\text{-}1)$$

To indicate which direction to rotate, the PW associated with the extreme position in that direction is sent instead of the associated angle position. The controller accepts commands in the form "# (servo number) P (position in pulse widths) S (speed to move in pulse widths per second) ". To move Servo 1 from a pulse width of 1300 μs to 1500 μs in 0.5 sec, the speed would be 400, and since the max pulse width is 2300 μs for that motor, the command would be "#1 P 2300 S 400". After that 0.5 second increment, the motor will reach its desired position, and a new command will then be sent to that servo.

This form of velocity control incorporates a certain amount of drift in the system which must be accounted for. The clocks on the computer do not send the signal at exactly the right time and so overshooting and undershooting the angles may occur. Consequently, whenever the action file tells a servo to pause at a given position, a position command is sent to the servo instead of a velocity command. This means that instead of sending the servo the PW associated with one of its extremes, the position directly associated with the desired angle is sent. Since most actions incorporate multiple pauses for each motor during their routine, this method has proved effective in minimizing the drift and overshoot caused by velocity control.

In order to further smooth out the motions, via-point trajectory generation is also incorporated into the controller. Instead of moving linearly from one position to the next, via-point trajectories ramp up/down the speed of the motor. Some via-point trajectories try to incorporate all via-points into one equation, but since there are numerous via-points in each action file, individual trajectories were created between consecutive points. The equations for these trajectories require the initial and final positions and velocities,

$$\begin{aligned} q(t_0) &= q_0 \\ v(t_0) &= v_0 \\ q(t_f) &= q_1 \\ v(t_f) &= v_1 \end{aligned}, \tag{2-2}$$

where $q(t_0)$ is the initial position, $v(t_0)$ is the initial velocity, and $q(t_f)$ and $v(t_f)$ are the final position and velocity of the trajectory. The desired trajectory is specified using,

$$q(t) = a_0 + a_1(t - t_0) + a_2(t - t_0)^2 + a_3(t - t_0)^3, \tag{2-3}$$

where

$$\begin{aligned} a_0 &= q_0 \\ a_1 &= v_0 \\ a_2 &= \frac{3(q_1 - q_0) - (2v_0 + v_1)(t_f - t_0)}{(t_f - t_0)^2} \\ a_3 &= \frac{2(q_0 - q_1) + (v_0 + v_1)(t_f - t_0)}{(t_f - t_0)^3} \end{aligned}.$$

The correct initial and final conditions are calculated using the two points the trajectory is going between (q_0 and q_1) as well as the previous (q_p) and next points (q_n) in the action sequence. If q_0 and q_1 are the same value, the motor is paused and no trajectory is calculated. If q_p, q_0, q_1, and q_n are either a continuously increasing or continuously decreasing series, the trajectory between q_0 and q_1 is made linear. Otherwise, eq. 2-3 is used to create the trajectory.

Initial velocities are set to zero if the slope from q_p to q_0 is zero or if it has the opposite sign of the slope from q_0 to q_1. Otherwise the initial velocity is set to whatever the final velocity of the previous move was. The final velocity is also set to zero if the slope from q_1 to q_n is zero or if it has the opposite sign of the slope from q_0 to q_1. If the slope from q_1 to q_n has the same sign as from q_0 to q_1 a final velocity (v_f) is set to the average slope from q_0 to q_n as given by

$$v_f = \frac{q_n - q_0}{t_n - t_0}. \tag{2-4}$$

Figure 15 illustrates the type of initial and final conditions that are used to create the trajectories for a sample motion trajectory. The paused and linear sections on the chart do not use via-point trajectories, but the others do.

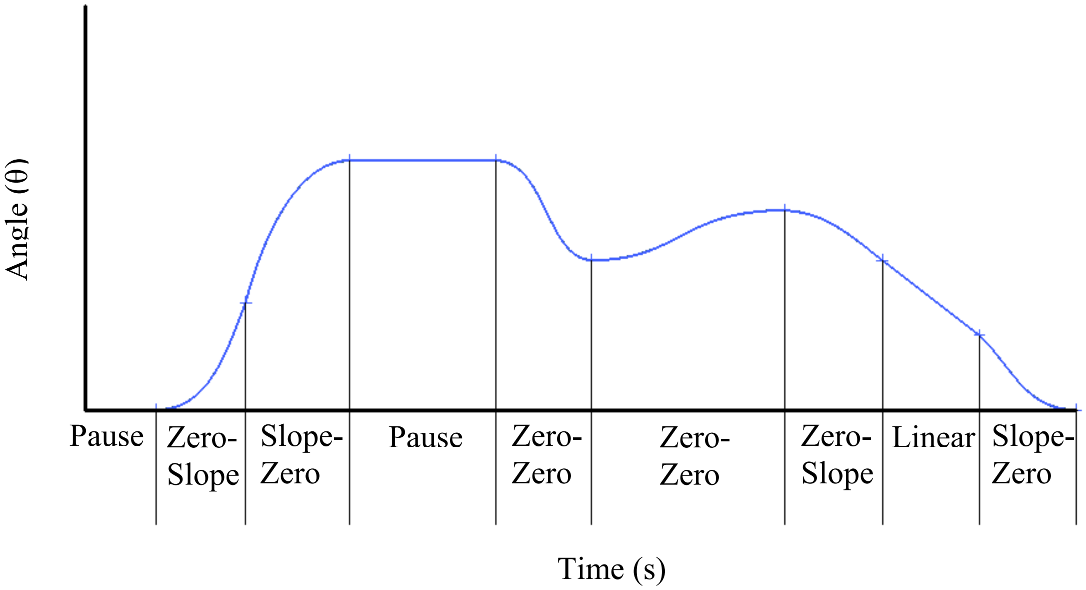


Figure 15: Types of Trajectories Generated. The terms refer to the initial and final conditions of the section, where the first term refers to the initial slope and the second term refers to the final slope. "Pause" means the servo pauses at that position and no trajectory is generated. "Linear" means the servo moves linearly from one position to the next. "Zero" means the slope is zero, and "Slope" means the trajectory has a non-zero slope for its initial or final value.

During each of these via-point trajectories, the motors are updated five times during the course of the curve. This is enough to allow the servos to speed up and slow down while limiting the drift that occurs. Motions shorter than 0.3 seconds are moved linearly in order to reach their desired positions on time and without significant drift.

Figure 16 is a plot of the commanded servo positions (in pulse widths) with and without smoothing effects for the action file BlowKiss.txt. Of note is the number of pauses each motor experiences during the action. As mentioned previously, at each of these pauses the controller sends a position command instead of a velocity command which accounts for the drift. Also, between the 4 and 5 second marks even the smoothed lines jump linearly from one point to the next. This is because the motion occurs over a small time step and a single command is sent instead of a series of smoothed commands.

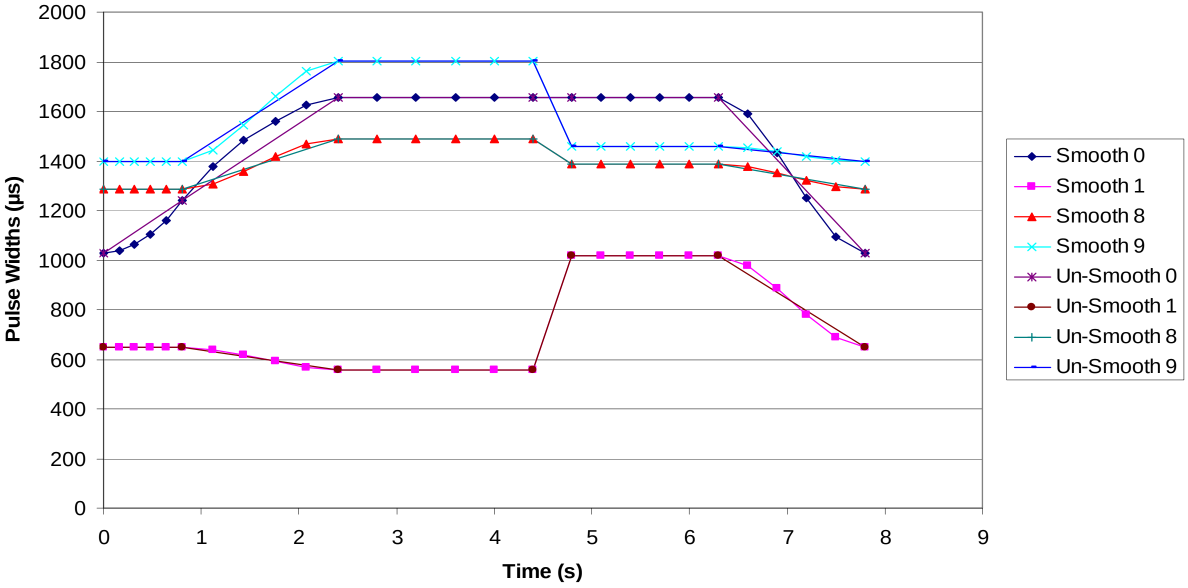


Figure 16: Effects of Smoothing on Motor Commands

Figures 17 and 18 show the velocity at the endpoint of the arm with and without these smoothing algorithms implemented. The data for these plots was gathered using the Cortex Motion Analysis system (an external motion measurement system that uses markers placed on the robot arm), and the velocities were calculated using the central difference method. As shown in the figures, the motors sped up and slowed down while using the smoothing algorithm but jumped to their respective velocities when no smoothing is used. Overall, these trajectories put less wear on the motors as well as make the robot run smoother than it would with a simple velocity controller.

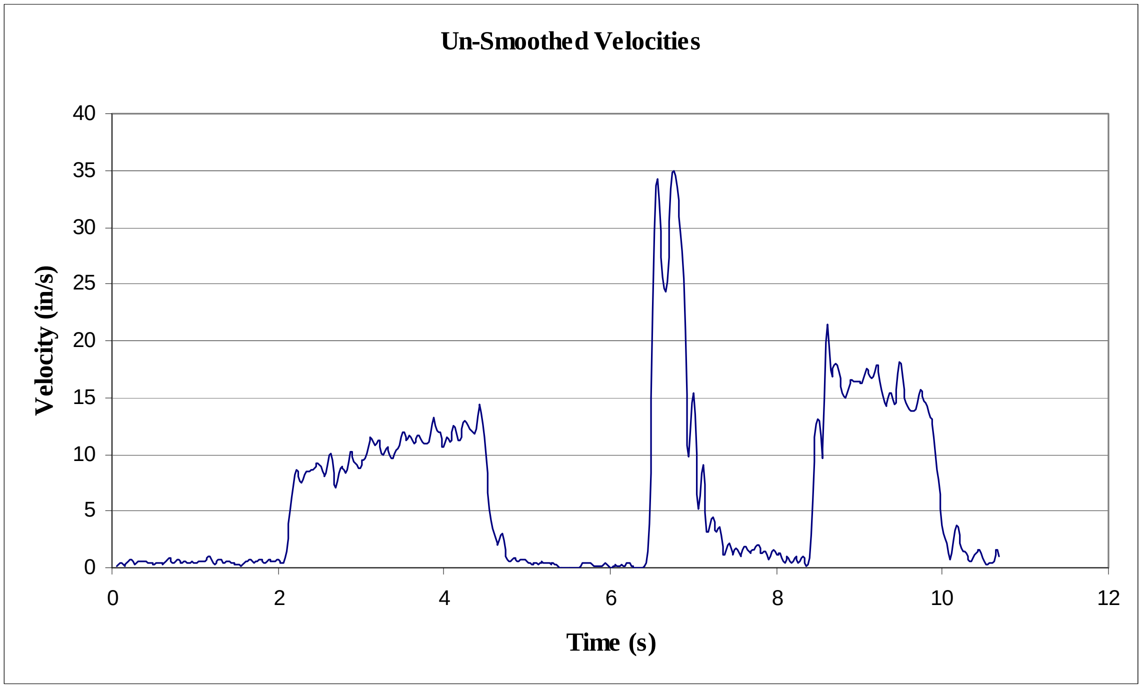


Figure 17: Endpoint Velocities without Smoothing

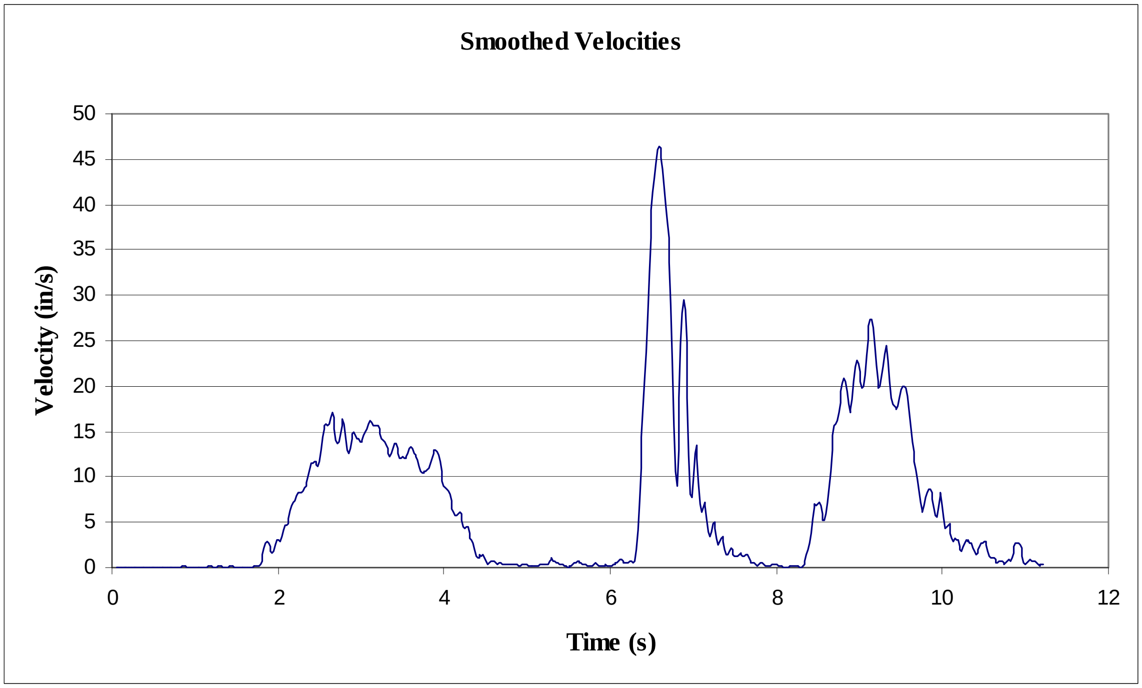


Figure 18: Endpoint Velocities with Smoothing

2.7 Testing

Troy was tested and evaluated to ensure it met with all of the performance and reliability requirements. The motors need to avoid overheating, rotate quickly enough for natural motion, respond promptly to new inputs, be repeatable, and be able to push and lift small objects in the clinic.

2.7.1 Temperature

To ensure that the servos do not overheat during use, the motors were tested to see how much their temperature increased during extended use. Since the two motors in each shoulder would have to do the most work, these were the motors chosen to be tested. In each case, the motor being tested was run through its entire range of motion on a constant loop for a half hour straight. The elbow was kept straight so that the motor would have to lift the entire arm as one cantilevered beam.

The shoulder flexion/extension servo (Servo 0) is a large servo, but it is the only servo in the arm that is not tightly mounted inside of the arm structure, which allows it to dissipate heat faster than the other servos. The temperature on the outside of the servo case before the test began was 75º F, and after a half hour it rose to 86º F. This temperature change was slightly noticeable to the touch, but did not appear to affect the motor's performance.

The shoulder adduction/abduction servo (Servo 1) is a smaller motor mounted tightly inside the plastic tubing used for the arm. This servo started at 73.7º F and after 10 min. it rose to 89.9º F. The temperature soon leveled off, and at 20 min. it was at 91.6º F. At the end of the 30 min., the motor casing reached 92.4º F. The temperature rose about twice as much as Servo 0, but a greater temperature increase was expected due to the lack of ventilation. This increase in temperature likewise did not appear to affect the motor's performance, and since these conditions are much more extreme than normal operating conditions, it is not anticipated that overheating will be an issue for these motors. Also, temperatures are cool enough so that if a child or therapist touches the motors, they will not be hurt.

2.7.2 Position Repeatability

Troy's repeatability was tested to ensure that it would consistently and reliably be able to perform its commanded actions. To test its repeatability, Troy was evaluated using the Cortex Motion Analysis system (as shown in Figure 19) in which the silver motion analysis markers are visible on the arm. The arm was commanded to move and hold still at two distinct positions while the 3D coordinate of the end of the arm was followed. Troy repeated this motion 10 times to evaluate how precise the system is.

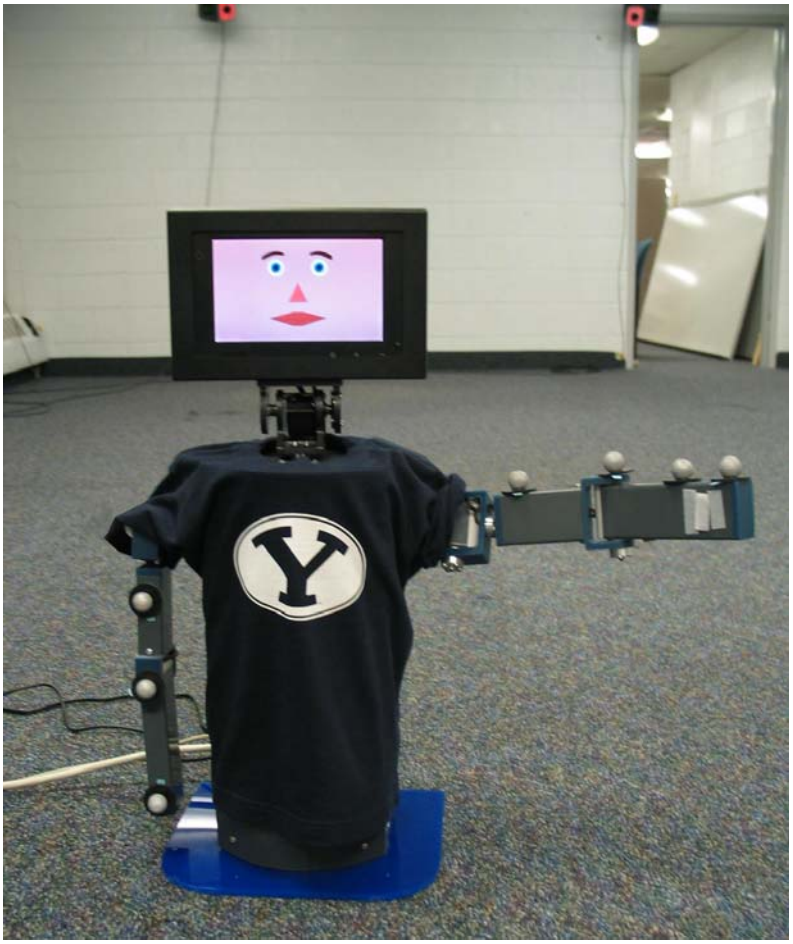


Figure 19: Troy Being Tested on the Motion Analysis System

In all ten repetitions the endpoint coordinate of the first position fell within a cube of 0.10” x 0.05” x 0.07”. In fact, two of the points were even measured to be identical. The Cortex system has an average residual error of 0.028 in., but the error can reach as high as 0.079 in. Since the points are nearing the limits of the cameras’ resolution, this explains why two of the points were measured to be the same. The locations of all 10 repetitions of the first point are shown in red on Figure 20.

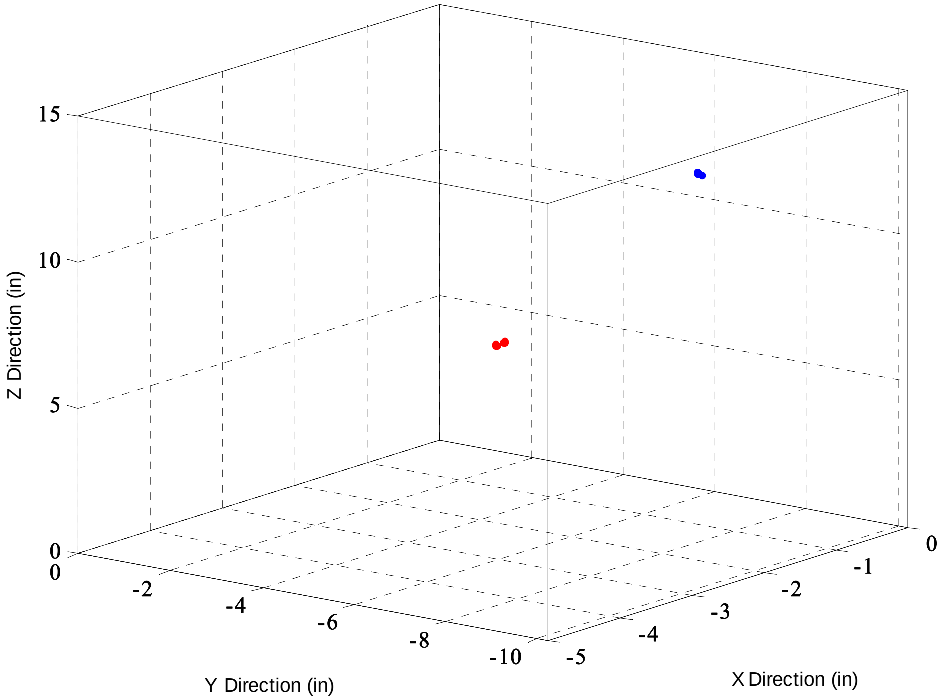


Figure 20: Repeatability Positions

The second point (shown in blue in Figure 20) was even more precise than the first. Only 4 distinct points were measured and the other six were repeats of those four. The repeatability was nearing the limits of accuracy of the Motion Analysis System, with all points falling within a 0.02” x 0.06” x 0.06” envelope. Together this test shows that Troy is repeatable to within 0.1” precision, and since that level of precision is hardly noticeable to the eye, it is sufficient for our applications.

2.7.3 Angular Velocity

All four arm joints were also tested on the motion capture system to see what the maximum angular velocities are for each motor. Table 2 shows the maximum angular velocities of the joints along with the manufacturer’s specifications on the maximum angular velocity with no load. These velocities are fast enough for naturalistic motion, but not so fast that they become dangerous for the children and therapists to be around.

Table 2: Maximum Angular Velocities for Motors

Joint	Max. Angular Velocity	No Load Specifications
Shoulder Flexion/Extension	296.4 °/s	428.6 °/s
Shoulder Adduction/Abduction	369.7 °/s	500.0 °/s
Humeral Rotation	443.8 °/s	461.5 °/s
Elbow Flexion/Extension	481.0 °/s	461.5 °/s

2.7.4 Frequency Response

In order to evaluate the frequency response of the motors, the arm was commanded to move in a sinusoidal motion with differing frequencies. The amplitudes of the angles were captured using the motion capture system. Figure 21 shows a Bode Plot of the frequency response of the shoulder flexion/extension motion. Typically the bandwidth of a motor is evaluated by seeing at what frequency the output reaches -3 dB. In this test the amplitudes never reached that level; however, at 2.5 Hz the motors were no longer able to keep the arm fluctuating around its central location. The motors were not able to overcome gravity, and the sine wave descended more than it rose each cycle, until it began pointing straight down. Even though, in practice, these motors will be lifting against gravity, if this test were to be repeated, it would be better to put the robot on its side and not fight gravity. Overall, the motor is able to function properly between 0.3 Hz and 1.8 Hz

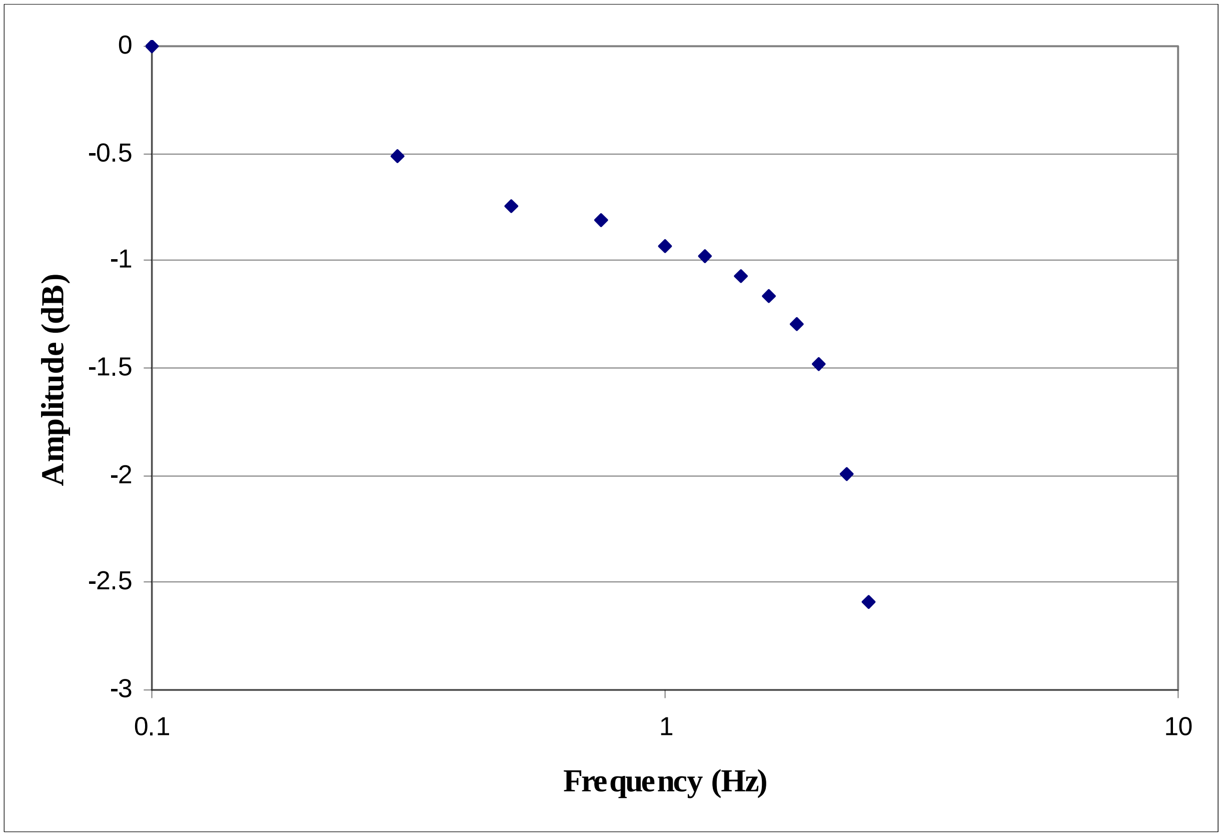


Figure 21: Frequency Response for Shoulder

A frequency response was also evaluated for the elbow motor. Figure 22 shows the Bode plot for the elbow where measured frequencies range from 0.1 Hz to 2.75 Hz. At 2.75 Hz the elbow began to behave erratically with inconsistent amplitudes, and so even though the amplitude never went below -3 dB, the test was stopped because the data began to be unreliable. The amplitudes were not constant within a given frequency above 1.8 Hz, and so this motor also functions properly from 0.3 Hz to 1.8 Hz.

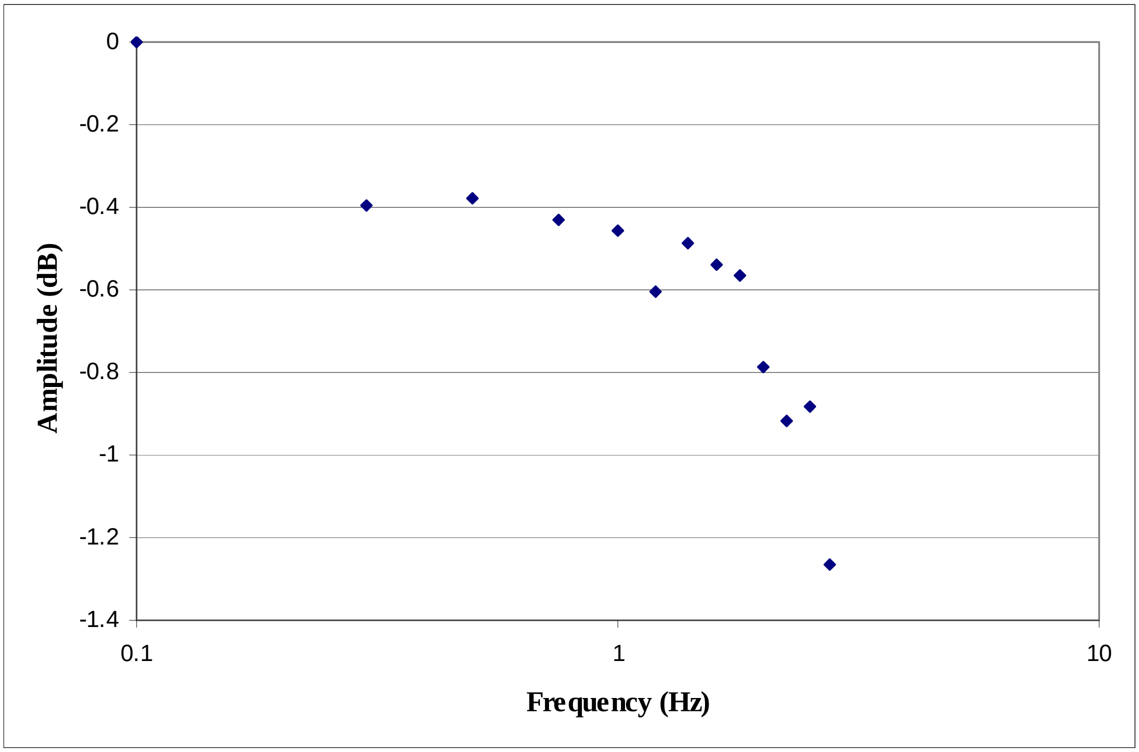


Figure 22: Frequency Response for Elbow

2.7.5 Force

Troy's arms were tested to see what types of force outputs they can generate. These forces were measured using a load cell that Troy pushed on to evaluate its force capabilities (see Figure 23). When pushing the load cell in front of Troy's body it measured 0.83 lbs which is sufficient to push small toys and balls. Troy can also push down with 1.08 lbs of force and to the side with 1.45 lbs. Above this level, the elbow joint cannot hold its position any longer, and so Troy should not try to lift or push objects with a force greater than 1.0 pounds. The load cell measured static forces, and during rapid motion, the dynamic forces would be greater. Although these dynamic forces would not be more than a few pounds, for the children's safety, it is important for the clinicians to prevent the children from being hit by the robot during motion.

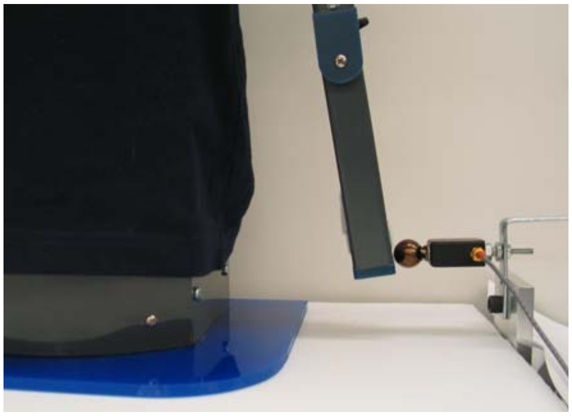


Figure 23: Force Testing with a Load Cell

2.8 Cost

One of the goals in building Troy was to keep the costs low. The materials cost around $1750, and together with tax and shipping, the total neared $2000. Although these costs are significant, they are still much less expensive than the alternative: using DC motors, gearboxes, and encoders. Machining and labor costs to assemble another robot could cost on the order of $1000. The following Table 3 shows the breakdown on costs.

Table 3: Supplies Cost

Materials	Cost
RC Servo Motors	$850
Motor Accessories	$230
Plastic Stock	$175
Screen	$220
Frame	$75
Power Supplies	$100
Misc. Supplies (Wii™ remote, cables, fasteners, etc.)	$100

3 CLINICAL TRIALS

Although it is up to the clinicians to ultimately decide if Troy is a useful tool in a therapy setting, this section will share some of the preliminary results and observations made in these initial trials.

In all cases, these trials were performed in the same therapy room in the BYU Comprehensive Clinic. The room is 10’ x 12’ x 8’ tall. There is a camera mounted in one corner of the room that can record the session as well as feed the video to another observation room. In the opposite corner of the room are a small counter and cabinet where the laptop is placed and subsequently connected to Troy. The specific setup of where Troy is placed and where the clinicians and children sit varies from session to session.

The clinicians involved in these initial trials are graduate students Maggie Hansen and Aersta Acerson from the Department of Communication Disorders at BYU. They are trained to provide therapy for children with developmental disabilities, and they work under the direction and supervision of the clinic director, Ms. Lee Robinson, and Communication Disorders professors Dr. Bonnie Brinton and Dr. Martin Fujiki. Each of these supervisors has years of experience working with children with autism and other disorders, and they have applied their knowledge towards facilitating robot-assisted therapy. These clinicians participated in the development of therapy protocols and activities for Troy to perform. Pushing objects in front of Troy, blowing a kiss, and tapping a tambourine are all examples of robot actions that were suggested by them. Their suggestions and feedback about robot size, design, and the GUI interface also helped mold Troy into the current system. The mapping of actions to specific buttons on the Wii™ remote was also performed in conjunction with the clinicians so that the control of Troy would be intuitive and easily executed without needing to look at the remote. For example, the therapists recommended that a single button cycle through a list of positive sounds to give it a more natural feel, and so that feature was incorporated. Throughout the course of this project regular meetings were held with the clinicians so that the final system would be a useful tool for them to help the children.

3.1 Clinical Trial with Typical Children

Troy was recently used in a pilot trial with two typically developing children without autism. The clinicians evaluated some of their therapy protocols to see what types of reactions Troy would elicit in the children as well as to see how well Troy could carry out these therapies. Children with autism will react differently than these typically developing children, and so this trial was designed to be used as a baseline to evaluate the feasibility of using Troy with children with autism. If the robot was too complicated and hard to use with typical children, then the added complications of using it with children on the autism spectrum would render it unusable in its current state.

The first child, A, was a 4 year old boy and the second child, C, was a 3 year old girl. Each child was brought into the therapy room with the robot placed on a table in the middle with chairs placed around it. Two therapists were in the room with the child. One directed the session and controlled the robot while the second was primarily there to work with the child, helping him/her perform the actions and preventing them from touching Troy. Child A interacted with the therapist and Troy through a turn-taking, imitation protocol wherein the therapist would perform an action, Troy would repeat it, and then the child was asked to perform the same action. Actions included raising both arms above the head, pushing buttons on a musical toy, pushing a button on a toy giraffe which made its neck grow, and hitting a tambourine. Child C also interacted with the robot and the therapist by taking turns playing a xylophone, pushing buttons on a musical toy (see Figure 24), and pushing the button on the toy giraffe. These interactions continued for about 10-15 minutes each.

Figure 24: Child C with the Clinician and Troy

Through performing these simple studies, we concluded that it is possible to control the robot during a clinical setting. The robot was able to perform useful interactions with the children, and it appeared that the children treated Troy as a social "other." For example, they waited for Troy to push the truck, held the xylophone up for Troy to play it, and watched Troy when they were to imitate what he had just done. When first introduced to Troy, child A appeared to feel anxious, but soon warmed up to Troy during the session. Child C was first surprised by Troy's autonomous movements, but also quickly became comfortable with it. Towards the end of the session, child A also seemed more interested in playing with the toy giraffe than with interacting with Troy. The child asked the help of the therapist to play with the toy and largely ignored the robot. Other researchers have noted that children on the autism spectrum are generally more interested in robots than their typically developing peers [24]; consequently, we are not overly concerned that this situation will happen frequently with children with autism. Also, since the goal is to enhance interactions between the children and others, if the robot's presence encourages the children to ask help directly from the therapist, this project is successful.

These children interacted socially with both the clinicians and the robot, which is encouraging for studies involving children on the autism spectrum. The clinician was able to send commands to the robot via the Wii™ remote she held in her hand, often out of sight of the child, and neither child appeared to notice that the clinician was controlling the robot. This could be useful since children with autism may fixate on the remote and want to control the robot themselves. It also demonstrated that with some practice, the clinicians would be able to learn the user interface well enough to control the robot in a clinical setting. Some of the observations made with typical children may not be similar to those that will occur with children on the autism spectrum; however, these results are encouraging and so further trials were continued.

3.2 Clinical Trial with a Handicapped Child without Autism

The first trial with a handicapped child occurred on 12 January 2010. The child in the study, L, is a 4 years, 7 months old boy who has developmental and behavioral handicaps, but is not autistic. Although he is non-verbal and has difficulty initiating interactions, he can use some basic signs to communicate and is able to attend to objects. He was chosen to participate in a pilot trial because he has some similar symptoms to children with autism, but he is still able to attend to the robot and the activities, which made it possible for the clinicians to test their protocols without worrying about keeping the child under control.

In L's first interaction with Troy, the robot was placed on top of a plastic box, about 10" high, which was placed on the ground, and the clinicians and child sat on the floor while interacting with Troy. They felt that Troy would be too high if it was situated on a table, and so they wanted to place it closer to the ground. They wanted Troy to push a toy truck off the box, and so that is why it was still raised off the floor.

When L first came into the therapy room, he was directed to sit on the ground next to Troy. L initially stared at Troy and appeared to be both anxious and nervous by it, but not so scared that he would not interact with it. The therapy protocol involved the clinicians, Troy, and L taking turns pushing a truck, tapping a tambourine, and pushing a button on a musical toy. L actively took his turns, and when asked whose turn was next, would often point to Troy or to the clinician leading the interaction. L clapped his hands and laughed when Troy completed his tasks, which showed that he enjoyed interacting with the robot. These interactions also showed that he treated the robot not only as a social other (demonstrated by his choosing Troy to perform actions), but also as a novel interaction (demonstrated by his reacting strongly to Troy completing actions).

It is important to note that these protocols are designed to encourage triadic interactions and self initiated behavior through imitation and turn taking activities. Everyone present took turns performing actions; L imitated what Troy and the clinicians did, and he was encouraged to bring others into the activity by asking him whose turn was next. These are some of the same focus behaviors that the therapists have for children with autism, which is one of the main reasons this was a useful trial.

In a subsequent trial with L, he seemed even more eager and less intimidated to play with Troy. In the second trial, L would wave back to Troy when it waved at him which he did not do during their first interaction. On this occasion, L actively brought the second clinician into the interaction for the first time. He also initiated interactions with both Troy and the clinicians much more frequently than he typically does. L is usually able to attend to activities fairly well, and the clinicians remarked that he was even more engaged in these interactions with the robot than usual. They also commented that he seemed to tire of the activities sooner than he did during his first visit, but that may have been due to the fact that he could see the toys from other activities and wanted to play with those as well.

Overall, these trials have given further encouragement to continue with studies involving children on the autism spectrum.

3.3 Clinical Trial with Children with Autism

Trials including children on the autism spectrum began on 8 February 2010. Child H, the first child with autism to interact with Troy, is an eight year old boy who has been receiving traditional treatment at the clinic. He exhibits many of the traditional behaviors associated with autism such as avoiding eye contact, not initiating interactions frequently, is unaware or uninterested in others around him, does not recognize emotions in others, and engages in self stimulatory behaviors such as flapping his arms and running around when he is excited. Compared with other children with autism, H is fairly high functioning. He is able to use and understand some language, can calm himself relatively quickly when he is over-stimulated, and does not exhibit many aggressive behaviors. Some of the therapeutic goals for H are to allow others to enter his circle of play, have him attend to clinicians' tasks, make and keep eye contact, initiate interactions, and use more language.

When H came in for his visit, he was first introduced to Troy, but then continued to participate in a traditional therapy while Troy remained in the corner of the room. This was meant to help H become accustomed to Troy's presence before any robot-assisted therapies began. Other researchers have used this familiarization stage so that the child is less fearful of the robot and is more interested in interacting with it before the robot-assisted therapy begins [17], [24]. When H first met Troy he appeared to be mildly interested in the robot but was soon directed to the other activities away from the robot. The familiarization period lasted roughly 40 minutes, and during that time H looked up and tried to touch Troy 3-4 times. On several other occasions H walked over to the counter where Troy was placed, but it is unclear whether he came to see Troy, or if he wanted his favorite toys out of the cupboard. In either case, Troy's presence did not seem to cause him any fear or anxiety. After the familiarization period the robot was brought to the middle of the room where it began to move and interact with H. The first time Troy moved, H was very excited and interested in the robot.

The portion of the session that included Troy lasted for about 10 minutes and consisted of activities such as waving hello and pushing a toy truck. As in the previous trial sessions, the therapists, Troy, and the child took turns waving or pushing the truck. H was often asked whose turn was next and he switched between picking the therapist leading the interaction and Troy. This triadic behavior continued throughout the session. H was highly motivated to participate in the interaction during the therapy session and would wave and push the truck as prompted. He even followed the clinician's instruction and sat down next to the robot for several minutes, which is also highly unusual for him. On multiple occasions he reached out to grab Troy's arm or head, and he consistently maintained eye contact with the robot during their interactions.

Troy was once again up on top of the box, and H seemed to especially like it when Troy pushed the truck off the edge of the bin. When the truck was pushed to him he would often pick it up and immediately position it in front of Troy, and he would then react strongly when Troy pushed it. One clinician commented that she had never seen H this excited, which indicates that Troy is a highly motivating tool; however, when he gets overly excited he sometimes stands up, flaps his arms, and walks around the room to self-regulate. The clinicians hope that with some more exposure he will remain interested in Troy but not exhibit some of these same over-stimulated behaviors, and even with these behaviors, they are highly encouraged by the robot due to its ability to engage the interest of H and increase his interaction levels. Overall H appeared to be very involved in the interactions, with Troy which may prove to be useful in enhancing the value of his therapy.

4 CONCLUSIONS

Using a robot as a tool in the clinical treatment of children with autism has been shown by multiple researchers to be useful in creating social interactions between the child and the therapist. During our preliminary trials, clinicians have observed this same trend with the robot Troy.

This thesis has explored the use of robots in autism therapy. It has done so by first evaluating the work of researchers around the world who have used robots with children with autism. These researchers have amassed a vast collection of experiments and therapies that can lead to better treatments for children on the autism spectrum. Through implementing the suggestions and observations of these researchers, the robot Troy was designed, built, and programmed to be engaging to the children. Troy was tested and was shown to work reliably. It was then implemented in a clinical setting with multiple children with differing developmental levels ranging from typically developing children to children on the autism spectrum. In all cases Troy was shown to be intriguing, and it encouraged interactions with the children.

The lack of generalization of skills practiced in robot-assisted therapy sessions performed by other researchers led us to the hypothesis that it is critical to incorporate the robot into a therapy involving and centered on trained clinicians, rather than centered on the robot. Transfer is never something that is easily achieved for children on the autism spectrum, but significant levels of generalization have been achieved when a therapist works with the child over a series of clinical visits. We feel that using the robot as well as a clinician will combine the benefits of having the intriguing robot present in addition to using methods already proven to help the children generalize what they learn.

The robot Troy has been used in the clinic with limited but promising results. The children that have been introduced to Troy have been interested in the robot and have interacted with it as a social partner. Therapists working with Troy were able to control it effectively during a scripted series of behaviors, and they observed that the children tended to be more engaged in the therapy than usual. They also noted that a child with disabilities that is not on the autism spectrum initiated interactions more than usual and brought others into the activity as well. Many of the observations made with this child were also seen with a child with autism. Both the child with disabilities other than autism and the child with autism were more engaged with the robot than they typically are during therapy, and both tended to react more strongly when Troy completed a task than when a clinician did. It is hoped that in further trials with child H, and with other children on the autism spectrum, that the same types of self initiated behaviors that were witnessed in the initial trials with the child without autism will also be seen. Further clinical trials will be necessary to evaluate the ultimate usefulness of a robot in helping children with autism, but these initial results are encouraging. Troy appears to be a positive addition to the clinic, and consequently, Troy will continue to be used as therapists evaluate the benefits of robot-assisted autism therapy.

4.1 Contributions

This thesis reflects some of the foundational work in robot-assisted autism therapy performed at Brigham Young University. It is an important element in support of a larger program involving researchers and clinicians from multiple fields. Development of the robot

Troy was a necessary first step in establishing this program. This master's research was therefore critical to the research and therapeutic objectives pursued at BYU. Furthermore, the robot and subsequent clinical research will benefit the field as a whole as our research team develops treatment methods to help children with autism.

The specific contributions of this master's research include:

- An extensive literature review on the subject of robot-assisted autism therapy for use by clinicians and researchers at BYU. Much of the literature review and observations regarding trends in robot-assisted autism therapy were published in a paper in the 2010 *IEEE International Conference on Robotics and Automation* [41].
- The development of design objectives for a humanoid robot to be used in autism therapy. These objectives were developed in consultation with members of our interdisciplinary team, including faculty and research assistants from the Department of Computer Science, Department of Communication Disorders, and Department of Psychology. Our research approach and design considerations were published in the 2009 *AISB New Frontiers in Human-Robot Interaction Symposium* [3], and in a paper that has been submitted to the 2010 *IEEE International Conference on Systems, Man, and Cybernetics* [42].
- The design and construction of a 10 degree of freedom upper body humanoid robot for use in the clinical treatment of children with autism. The robot is equipped with a computer monitor face and audio speakers to enable communication with the children. The robot is capable of performing the interaction activities designed by the therapists.

- Development of a controller to actuate the robot joints using via-point trajectories and velocity control.
- Thorough laboratory testing of the robot's functionality and performance. These experiments verified that the robot has the range of motion, speed, repeatability, and force capabilities to perform well in a clinical setting.
- Development of a library of robot actions that is available to the clinicians to use in therapies. These actions can be selected, concatenated, and modified using a graphical user interface developed in conjunction with researchers in the Department of Computer Science.
- Placement of the robot in an autism clinic and support of the pilot studies involving two typical children, one non-autistic child with disabilities, and a child with autism. Results of these initial studies suggest that the robot will be an effective tool in engaging children with autism in meaningful interactions with therapists.

4.2 Future Work

Future work will focus on using Troy in the clinic to help these children with autism. H, along with other children, will continue to interact with Troy as clinicians evaluate whether the robot's presence has led to more or less generalization than traditional therapy. Troy will continue to be used in the same way it is currently being used, but it may later incorporate emotion recognition activities along with other new actions and sounds.

The user interface will continue to be developed so that the robot is easier for the clinicians to use. Clinicians currently rely on programmers and engineers to program robot actions into the controller and to check that their choreographed action sequences are correctly strung together. Researchers in the Department of Computer Science at BYU are continuing these developments so that robot programming and sequencing may be more easily accomplished by clinicians.

Other robots will later be incorporated in these studies, including Trevor, a robot built from a Lego® Mindstorms kit, and a toy dinosaur robot named Pleo. Troy is currently the most advanced humanoid robot at BYU for use in this autism therapy, and that is one reason why it was used first. The Lego® robot is less expressive than Troy and has more restricted arm motion, but due to its relatively low cost and ability to be reconfigured, it has great potential for therapeutic benefit as well. Pleo is not humanoid and cannot imitate human social interaction, but it has been shown to be very expressive and engaging for people with and without autism.

Further studies involving different types of robots will help explore the connections between robots and children with autism. More understanding of these interactions could help both engineers and clinicians design, build, program, and use robots to better help children with autism.

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APPENDIX A. ARM CAD DRAWINGS

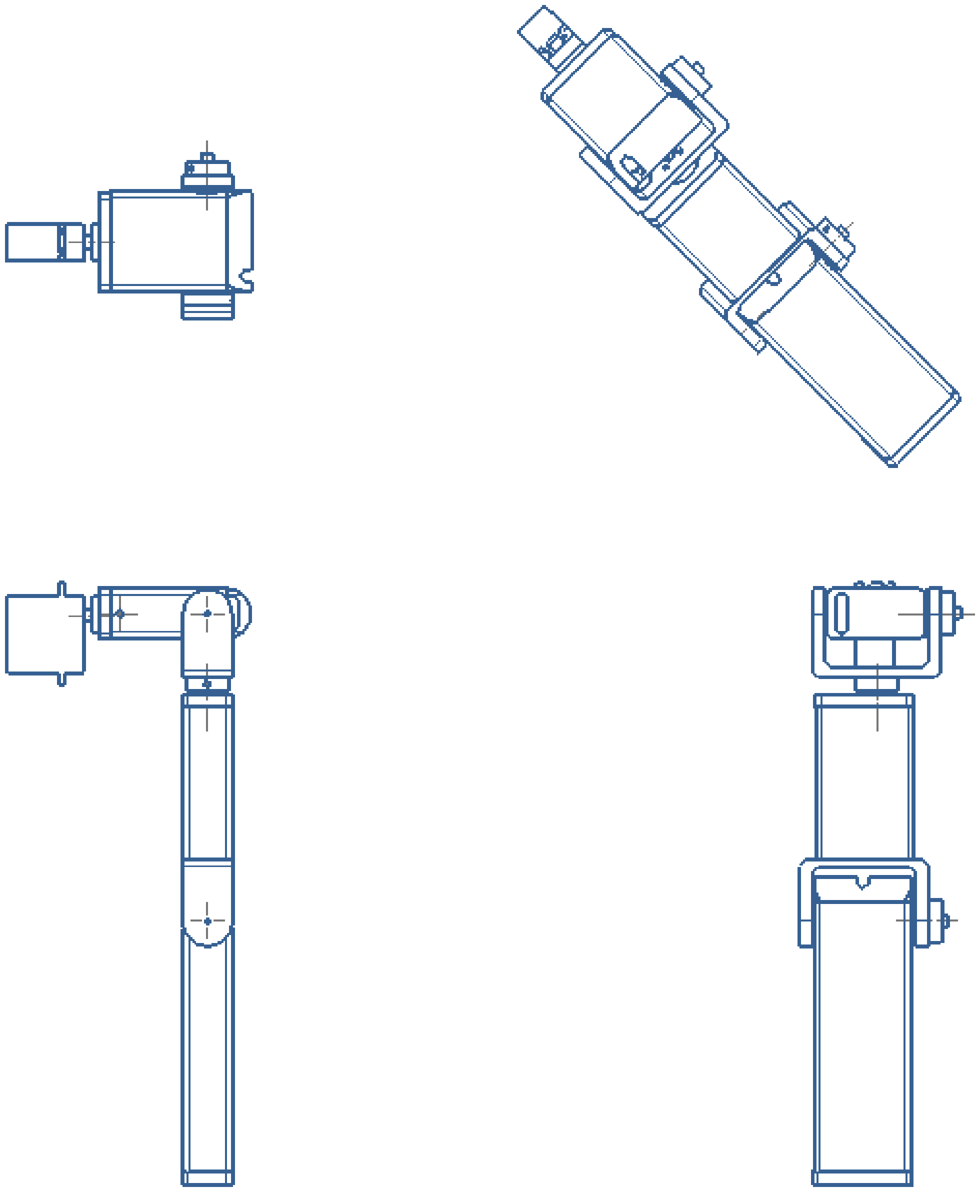

Figure A-1: Arm Assembly

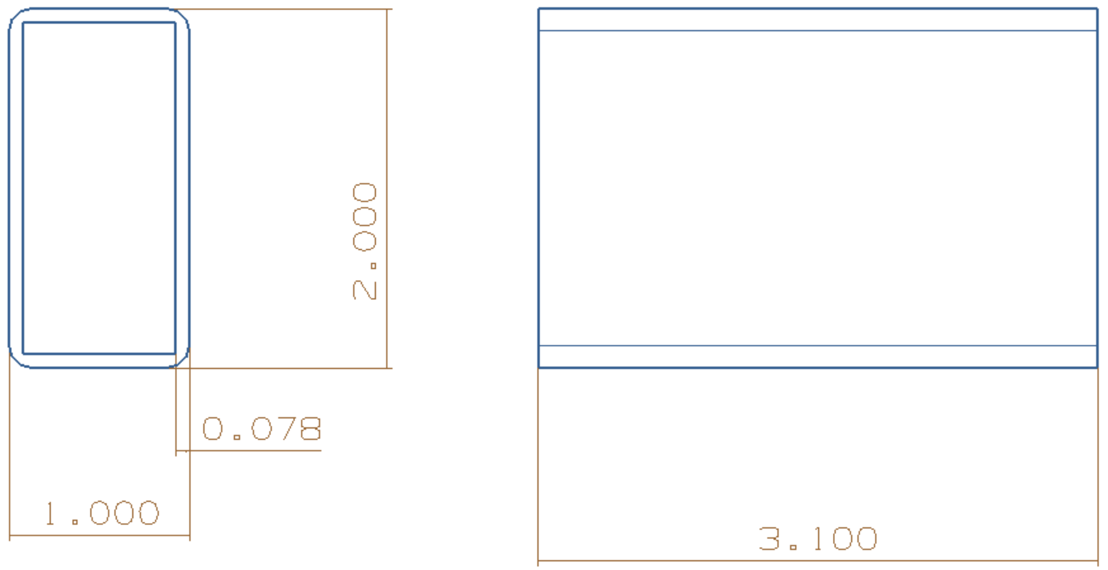

Figure A-2: Humerus Drawing

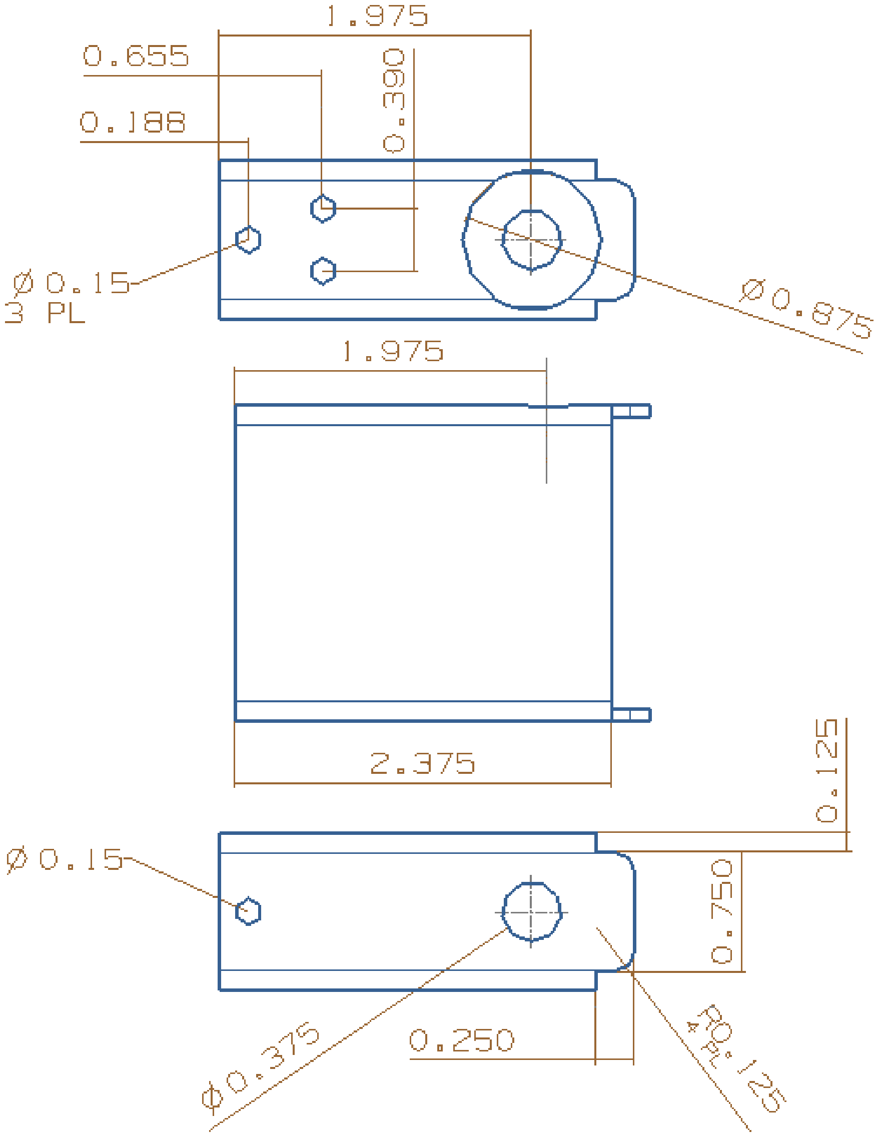

Figure A-3: Shoulder Drawing

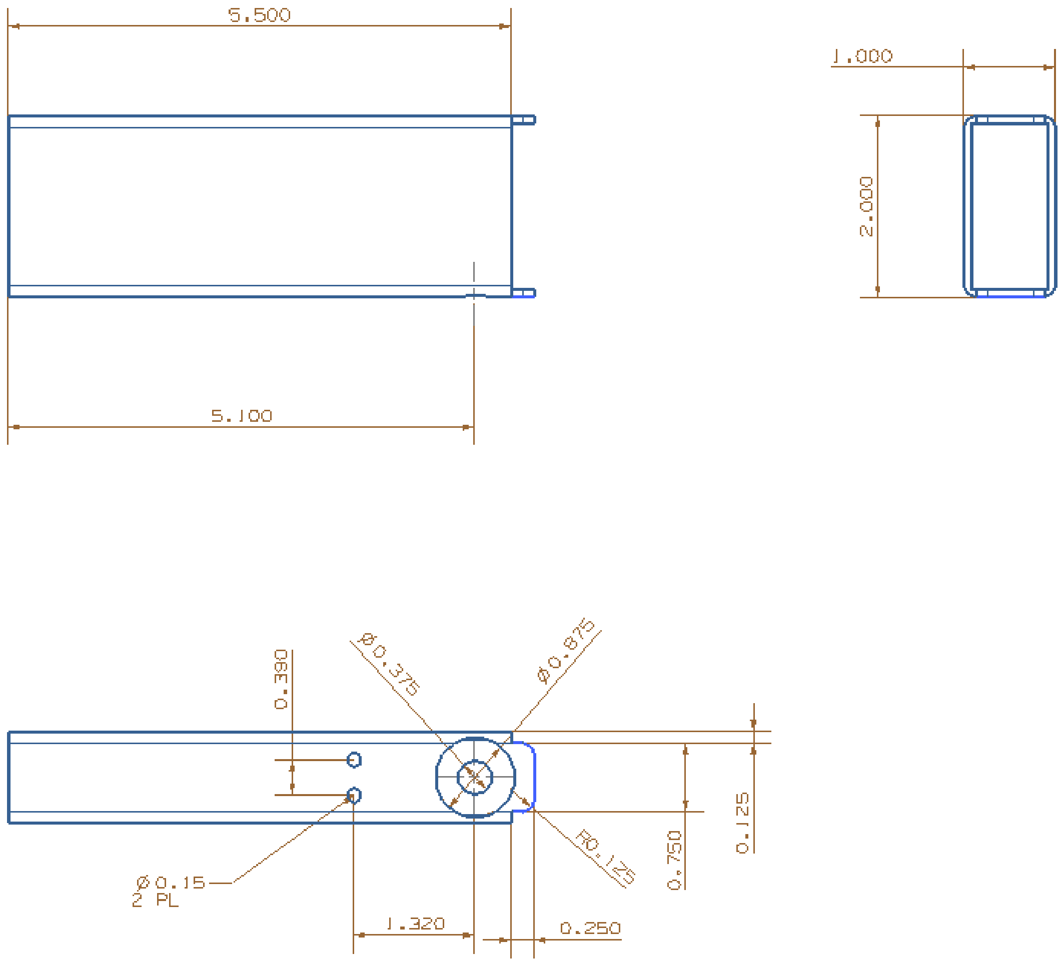

Figure A-4: Forearm Drawing

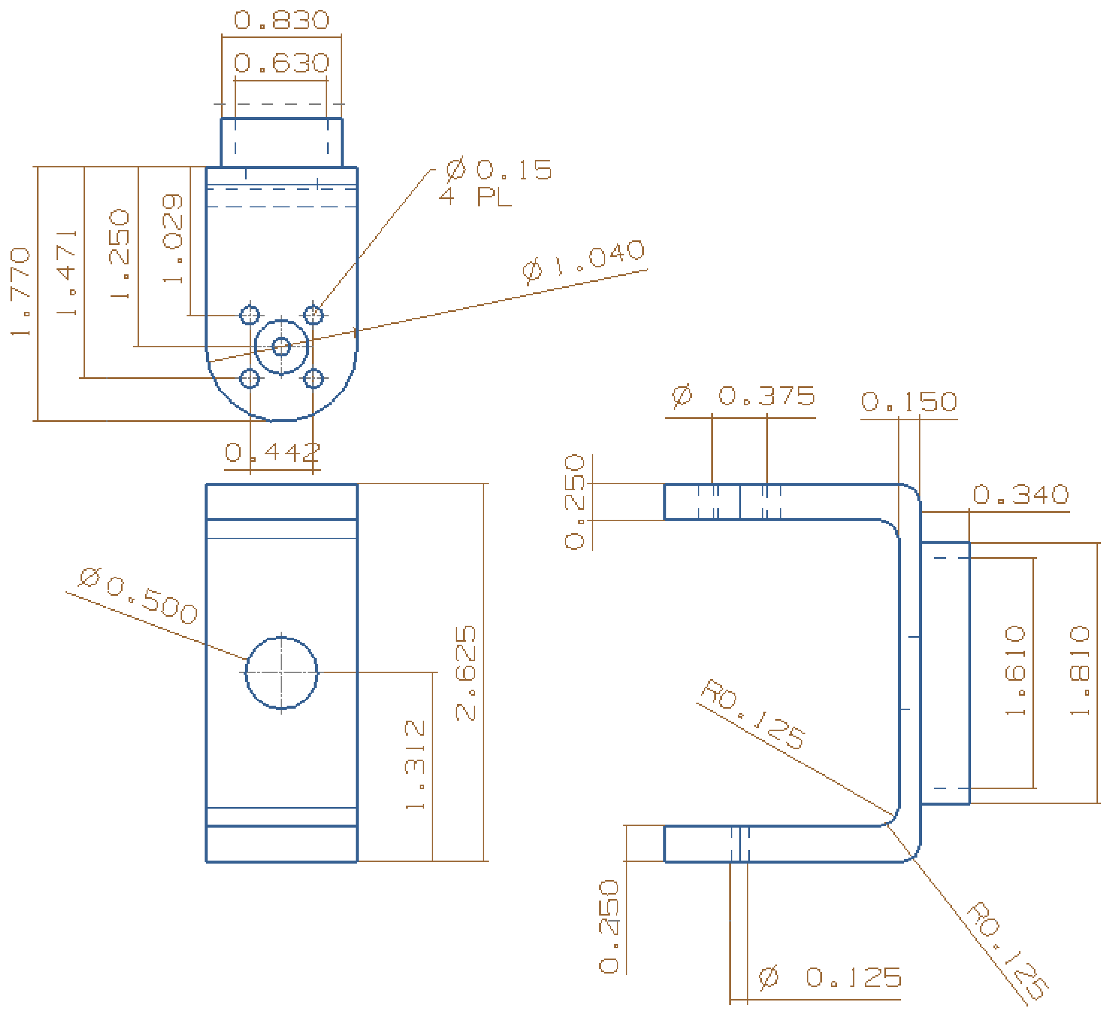

Figure A-5: Shoulder Joint Drawing

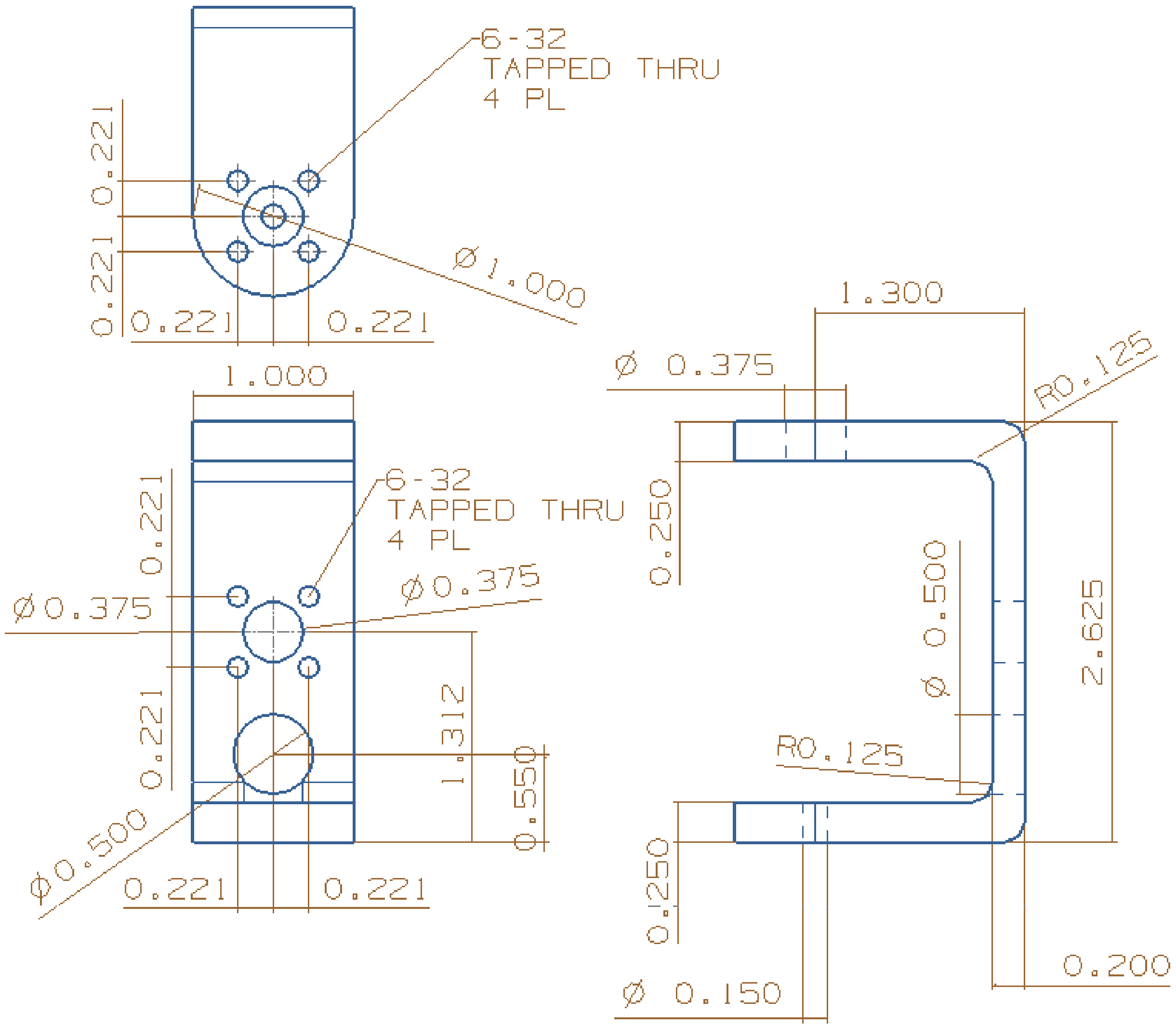

Figure A-6: Elbow Joint Drawing

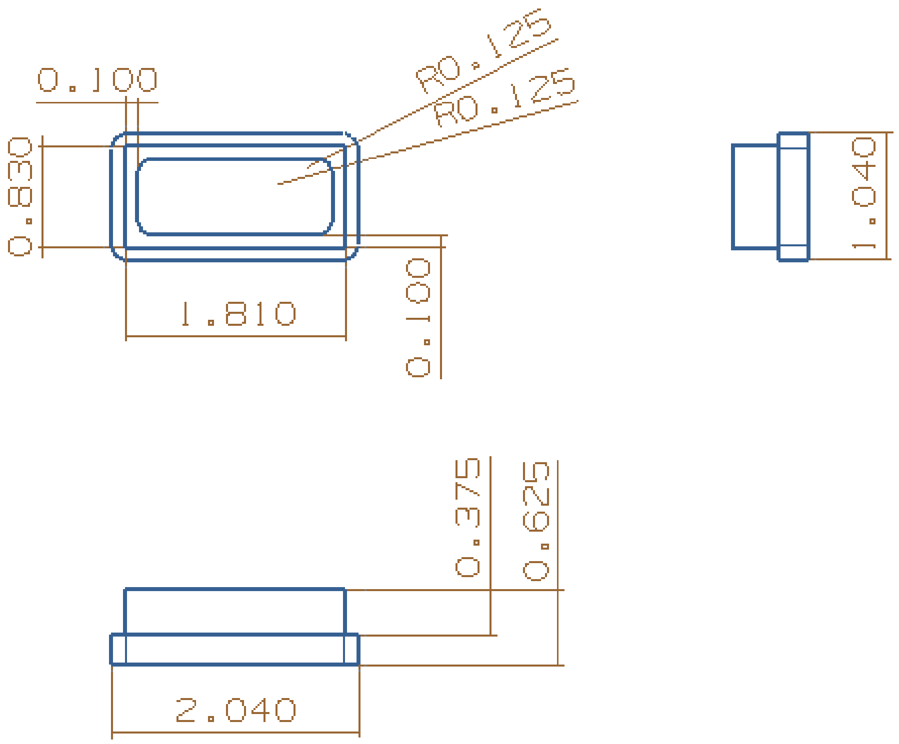

Figure A-7: Forearm Cap Drawing

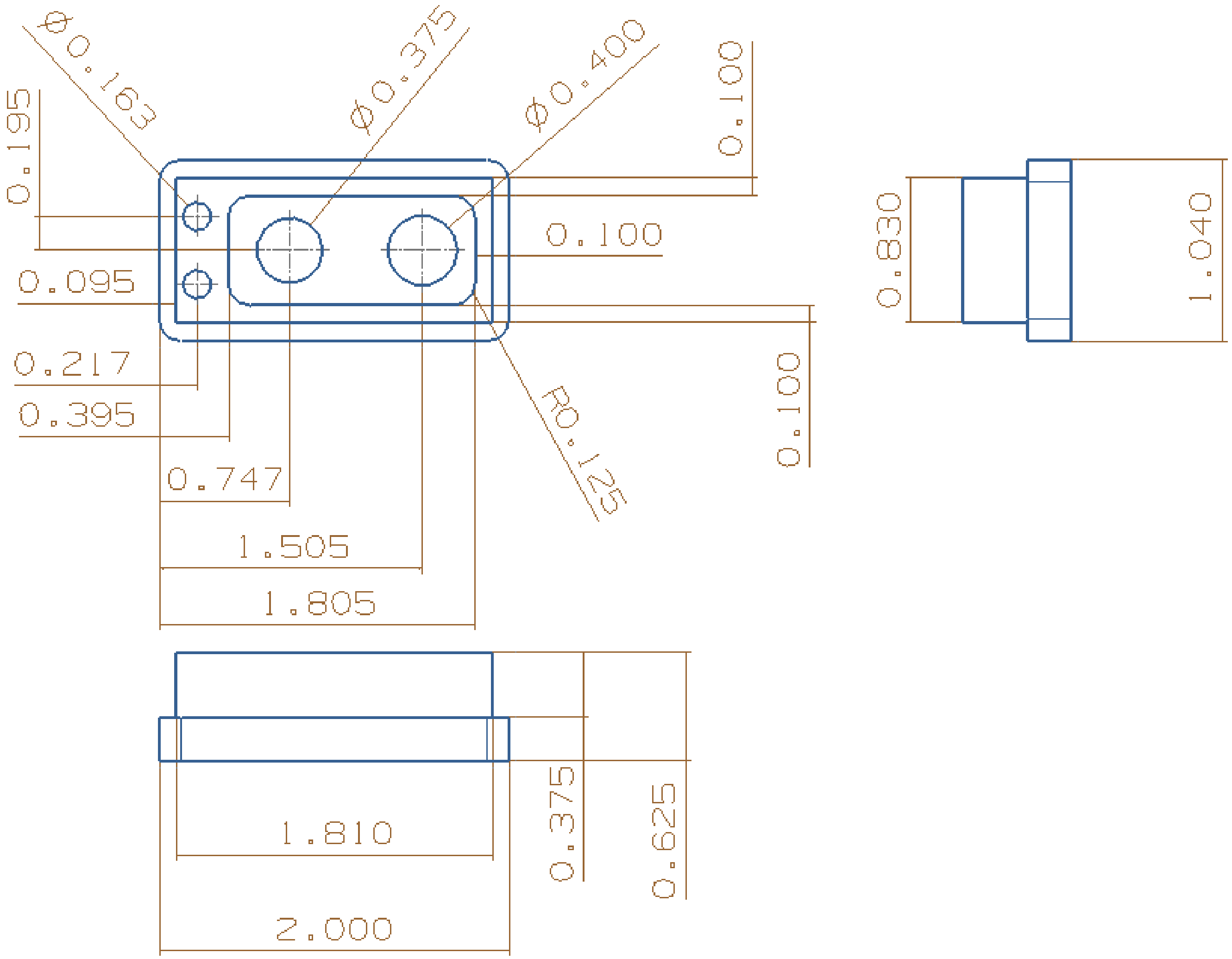

Figure A-8: Humerus Cap Drawing

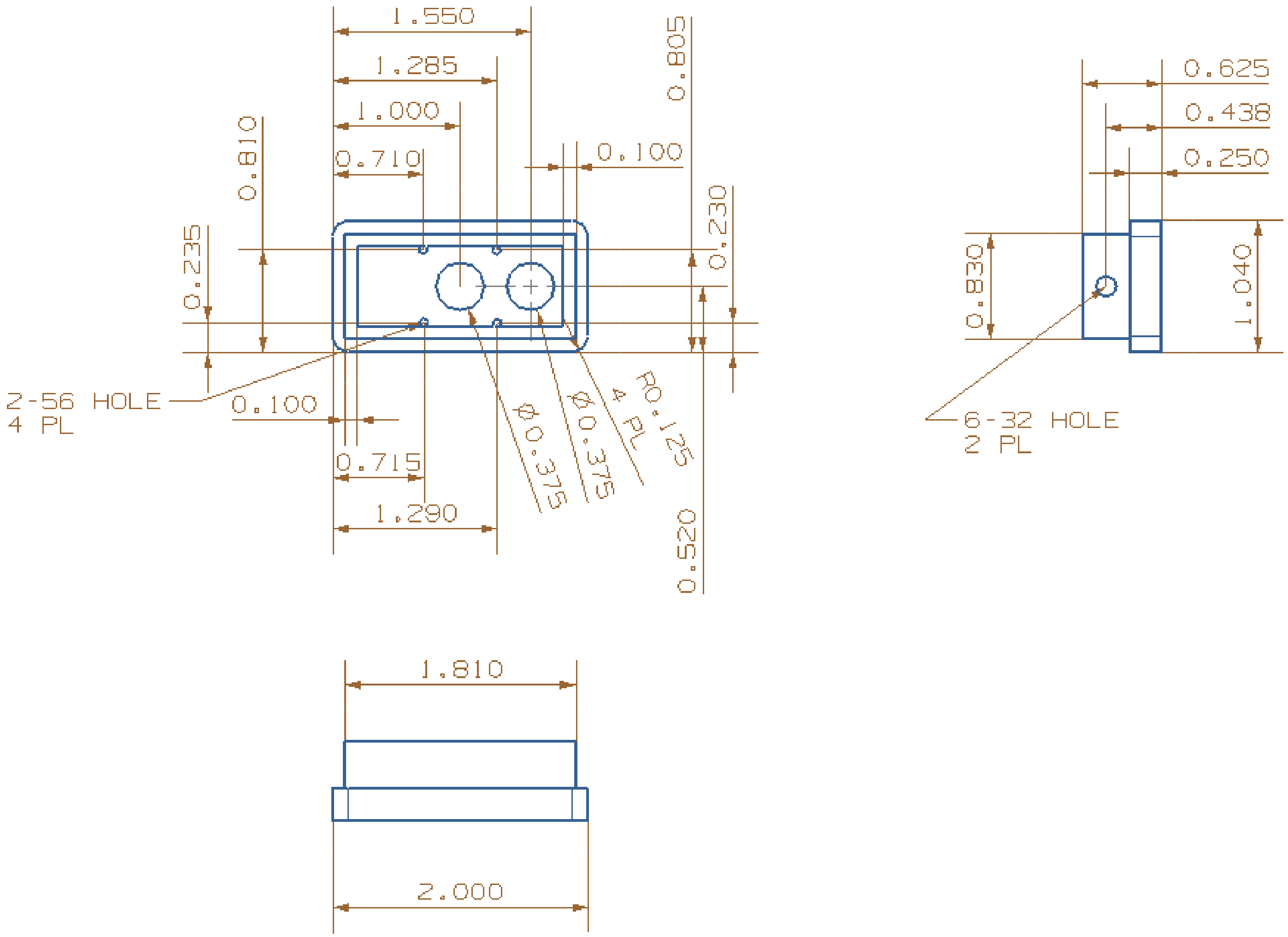

Figure A-9: Shoulder Cap Drawing

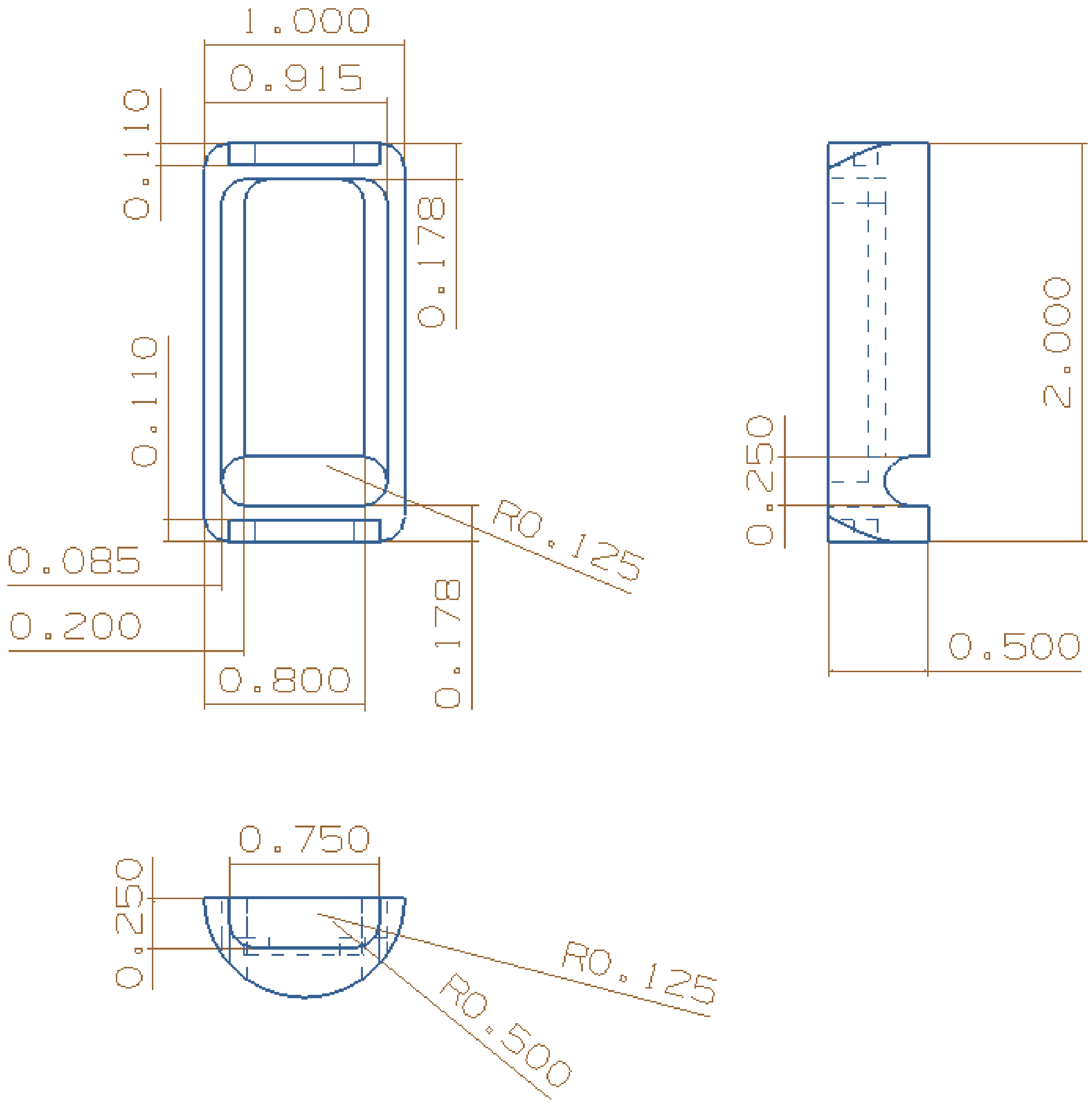

Figure A-10: Humerus Cover Drawing

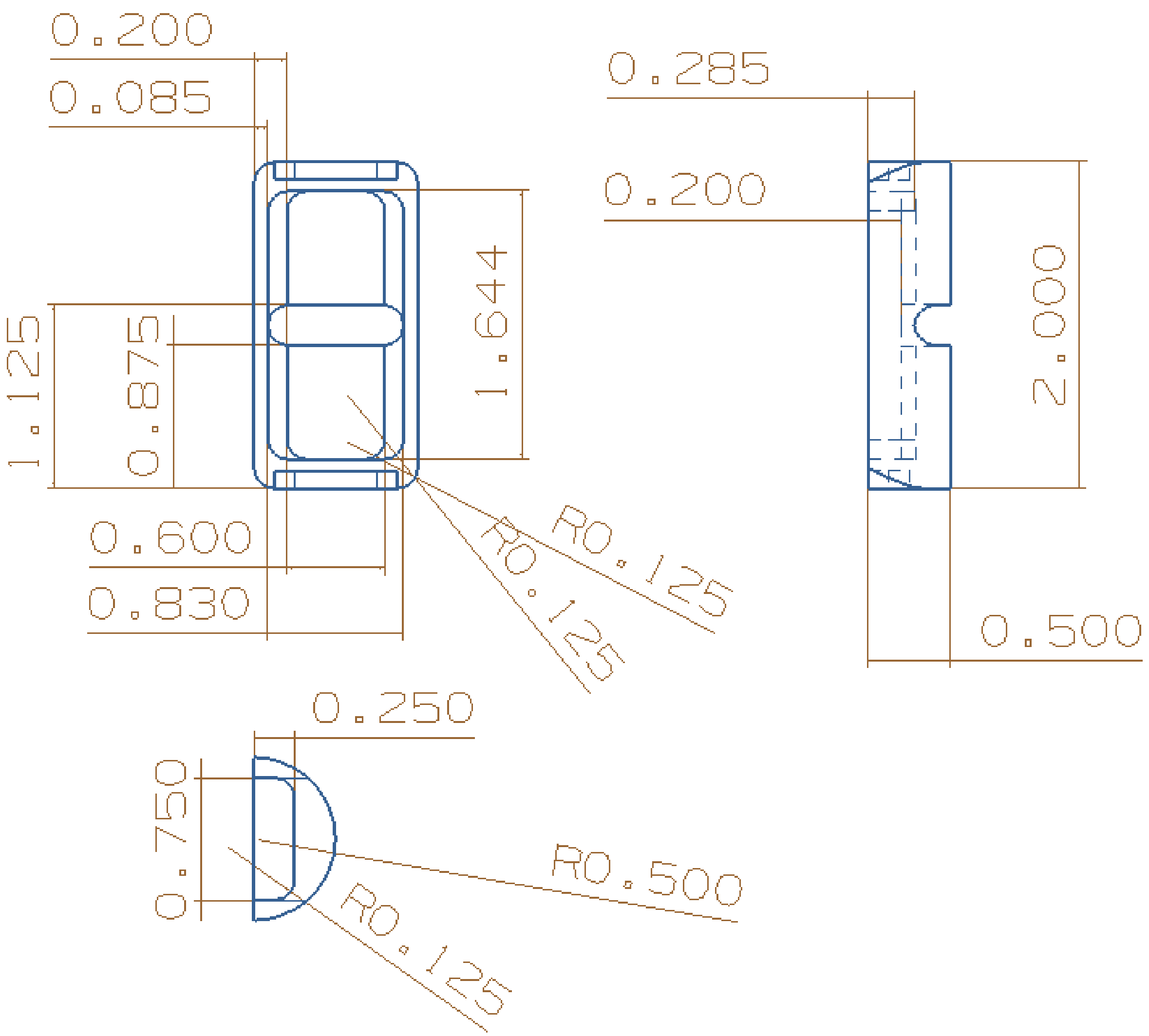

Figure A-11: Forearm Cover Drawing

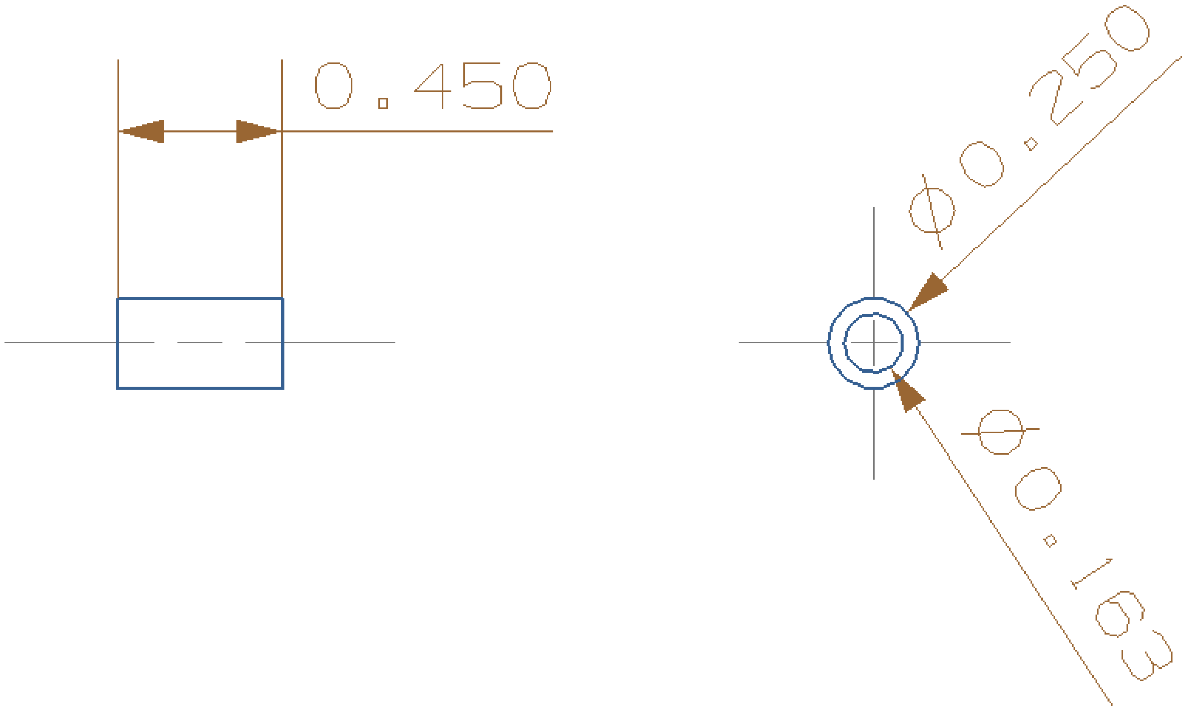

Figure A-12: Standoff 1 Drawing

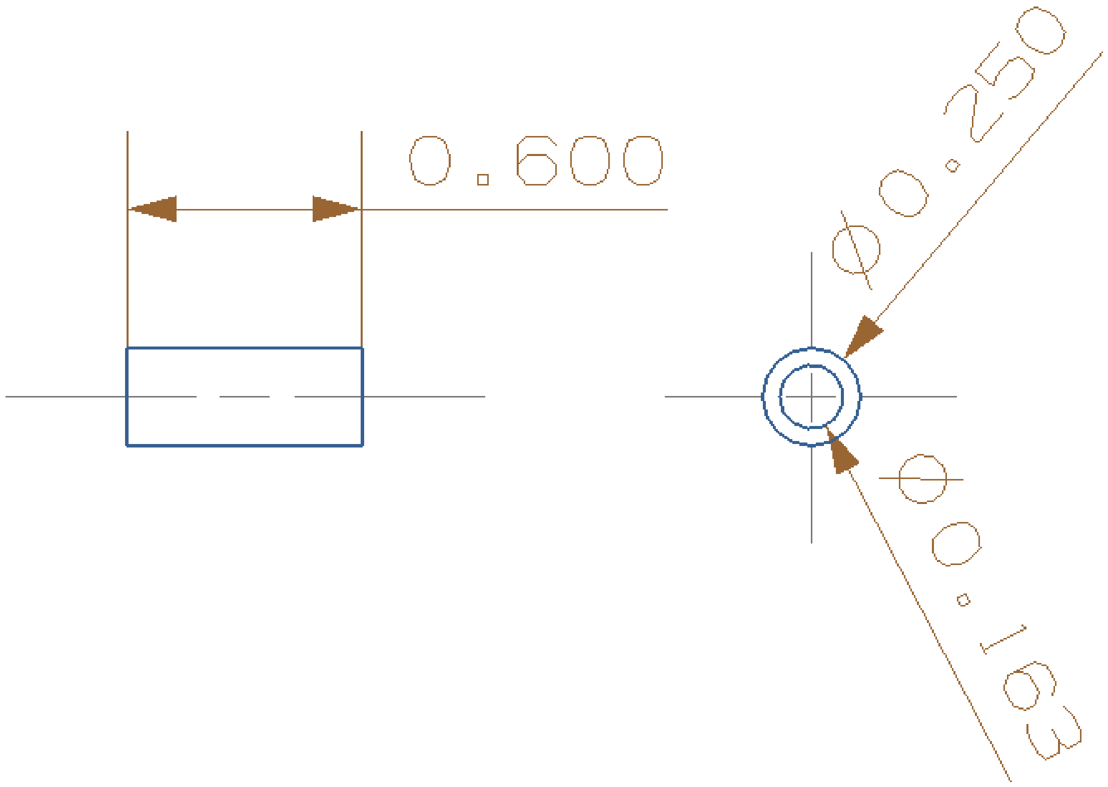

Figure A--13: Standoff 2 Drawing