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An Affordable Compact Humanoid Robot for Autism Spectrum Disorder Interventions in Children

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Abstract— **Autism Spectrum Disorder impacts an ever-increasing number of children. The disorder is marked by social functioning that is characterized by impairment in the use of nonverbal behaviors, failure to develop appropriate peer relationships and lack of social and emotional exchanges. Providing early intervention through the modality of play therapy has been effective in improving behavioral and social outcomes for children with autism. Interacting with humanoid robots that provide simple emotional response and interaction has been shown to improve the communication skills of autistic children. In particular, early intervention and continuous care provide significantly better outcomes. Currently, there are no robots capable of meeting these requirements that are both low-cost and available to families of autistic children for in-home use. This paper proposes the piloting the use of robotics as an improved diagnostic and early intervention tool for autistic children that is affordable, non-threatening, durable, and capable of interacting with an autistic child. This robot has the ability to track the child with its 3 degree of freedom (DOF) eyes and 3-DOF head, open and close its 1-DOF beak and 1-DOF each eyelids, raise its 1-DOF each wings, play sound, and record sound. These attributes will give it the ability to be used for the diagnosis and treatment of autism. As part of this project, the robot and the electronic and control software have been developed, and integrating semi-autonomous interaction, teleoperation from a remote healthcare provider and initiating trials with children in a local clinic are in progress.**

I. INTRODUCTION

Autism is a complex developmental disability that typically appears during the first three years of life and is the result of a neurological disorder that affects the normal functioning of the brain, impacting development in the areas of social interaction and communication skills. Statistics show that Autism Spectrum Disorder (ASD) is impacting ever-increasing numbers of children. The Center for Disease Control and Prevention estimates that an average of 1 in 110 children in the U.S. have ASD (www.cdc.gov). Autism is a spectrum disorder, which means that symptoms and characteristics can present themselves in wide variety of combinations from mild to severe.

Using the Diagnostic Statistical Manual, 4th Ed. [1], autistic disorder, 299.00, is diagnosed using specific criteria. The child who is to be labeled or classified as autistic must show delays in the development of: 1) social interaction, 2) communication and 3) behaviors. Social interaction includes non-verbal behaviors such as eye contact or gaze, facial expression, body posturing and gestures that regulate social interaction. In addition to characterizing ASDs, deficits in social behavior impact children's ability to function spontaneously and independently. Unlike typically developing peers who independently attempt, practice, and master social interactions, children with ASD have difficulty with awareness of the social world and as such do not independently develop capabilities with social interactions. Consequently, targeted social intervention is required in order to help children with ASD develop social capabilities.

In addition to delays in social skills, language and academics, children with autism often have delays in play. Children with autism often lack knowledge about the physical properties of objects, resulting in play that is limited in frequency, variety, and symbolic quality [2], [3], [4]. Technology can aid in diagnosis by producing visual and audio cues as well as recording the response of the child, and it can potentially perform these functions with more repeatability than a human could, making methods for more reliable diagnosis and treatment efficacy monitoring [5].

There is currently no specific cure, however there are treatment plans (biomedical, therapeutic and educational) to remediate the delayed development and ameliorate behaviors. No one method alone is effective in treating autism. The early education of autistic children [6], weighs heavily on behavioral and communication approaches seen in applied behavioral analysis (ABA). Many researches and practitioners have developed interventions to teach play activities to children with autism served through Early Intervention (EI) [7]. However, research is lacking in integrating robotics as an effective method of Early Intervention. Play has an important role in child development with many potential contributions to therapy, education and enjoyment, and play therapy can

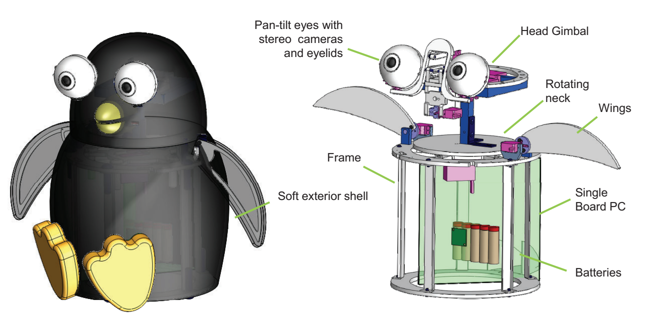

Fig. 1. Conceptual visualization and schematic drawing of the robot. This humanoid robot is affordable, non-threatening, durable, and capable of interacting with an autistic child.

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help improve communication skills [8]. Current therapy is limited in that it is expensive and difficult to have available frequently - it is typically restricted to a clinic or school setting. Since the school year is often 180 days, even school-based therapy leaves 185 days unaccounted for. Children with autism need constant instruction, which the proposed system can provide by enabling continuous home care, which could vastly improve the outlook.

Autistic children have been shown to imitate and have eye contact more frequently with robots. These behaviors are exhibited more often in treatment sessions that utilize robots [5]. In [9], the authors investigate how a small minimally expressive humanoid robot can assume the role of a social mediator - encouraging children with autism to interact with the robot, to break their isolation and importantly, to facilitate interaction with other people. They demonstrate that the robot effectively helped to mediate and encourage interaction between the children and co-present adults.

Kozima *et al* [10] designed a 4-DOF interactive robot Keepon to interact with children with autism where it worked as the pivot of triadic play with adults or other children. Giorgio et al. [11] presented an open systems platform, iCub, to support collaborative research in cognitive development. Distinctive from other robots, the robot presented here is based in part on our preliminary designs and previous research efforts [12], and takes on the form of a cartoon-like penguin and is named PABI: Penguin for Autism Behavioral Intervention (©*2011 Dickstein-Fischer*) as shown in Fig. 1. Being inexpensive to manufacture, robust, and easy to operate means that they could be made readily available to families of autistic children, making this autism therapy tool available for frequent and in-home use.

II. METHODS

A. Requirements

The proposed robot is designed to be a low-cost, compact, easy to use system that can be used the in the traditional school and clinic setting, but also brought home for enhanced continuous care. By enabling the robot to be brought home, the effects will be significantly amplified due to the increased interaction time that the child has with the robot. The robot will be able to be used as an autonomously acting "toy" to play with and interact with as described in [8]. But, it will also be able to be used in a teleoperated mode where a clinician can operate the device remotely (from within the same room or a remote site) and control the robot's motions while receiving video and audio streams. PABI may also be used to assist in diagnosis, assessment and charting where the robot can not only interact with the child, but also monitor the child's body and eye motions to assist in quantitative assessment. This assessment can be used to update and modify the robot's autonomous behavior as the child's level of interaction improves.

One primary goal was to make the robot robust enough to handle the rigors of being used as a toy at home. It therefore must withstand the sort of abuse inflicted on a stuffed animal by a child. This means it would have to survive being dropped, picked up by different parts, and have parts of it forced in all different directions. As such, special attention was devoted to the materials the robot was constructed out of and the ways in which each appendage was attached.

An annotated conceptual drawing of the robot is shown in Fig. 1. The cartoon-like penguin for that PABI takes on enables the use of human-like emotions, while remaining simple and non-threatening. The robot has 11 degrees of freedom: 3-DOF head/neck with 3-DOF for a pair of eyes and an additional 1-DOF for each eyelids, a 1-DOF beak, and 1-DOF for each of the wings. The head has cameras in each eye to assist in face-tracking, and the robot also has a speaker and a microphone for recording and interacting with the child.

B. Mechanical Design

The robot's main structure is composed of three main tiers: the base where the control and power electronics reside, the fixed upper level where the wings are located, and the rotating top level which holds the pan-tilt gimbal unit for the head. These tiers, as well as several servo motor mounts and other parts, were made from acrylic in this iteration of the robot due to its low cost and its ability to be cut on the laser cutter. The frame of the robot is shown in Fig. 2.

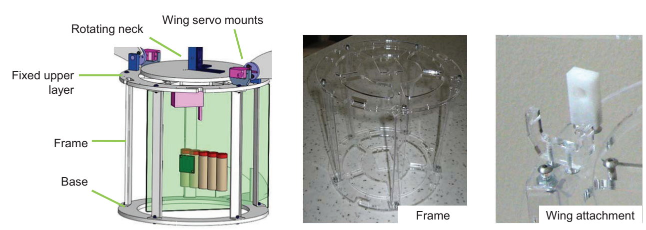

Fig. 2. The 3-tier acrylic frame of the robot.

1) Head and Eyes: The head achieves its tilt and roll from a gimbal as shown in Fig. 3. Servo motors move the gimbal, and dowel pins help it to rotate about the preferred axis. To improve the robustness of the design, high strength rare earth magnets hold the head plate to the gimbal; twisting and pulling abuse of the head will cause it to safely dislocate from the gimbal such that the servos do not get damaged as shown in Fig. 3 (right). Elastic cord keeps the head from separating entirely from the body. A servo pans the head, and it is protected from damage by the magnets in a similar fashion as well.

The eyes each have an independent rotation of $\pm 90^{\circ}$about the vertical axis so that they can pan left and right, and they have a coupled rotation of $\pm 45^{\circ}$about the horizontal axis so that they tilt up and down together providing 3-DOF with speeds controllable up to approximately $300 deg/sec$. A further 2-DOF includes independent control of eyelids. The servo that tilts the eyes is attached to the eyes with a four-bar linkage as shown in Fig. 4. The remaining servos that drive the eyes and eyelids are located within the eyes themselves. Making the eyes large enough to accommodate the servos enhances the intended cartoon-like appearance of the robot - large eyes are a typical feature of non-threatening cartoon-like creatures.

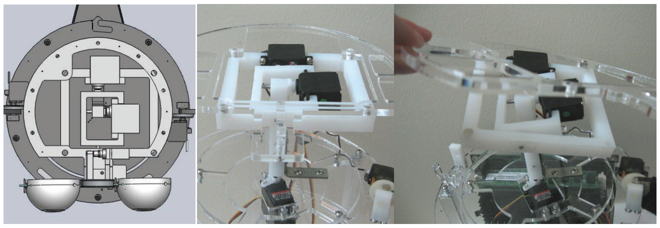

Fig. 3. Penguin head gimbal provides tilt and roll of the head and is mounted upon a neck rotation.

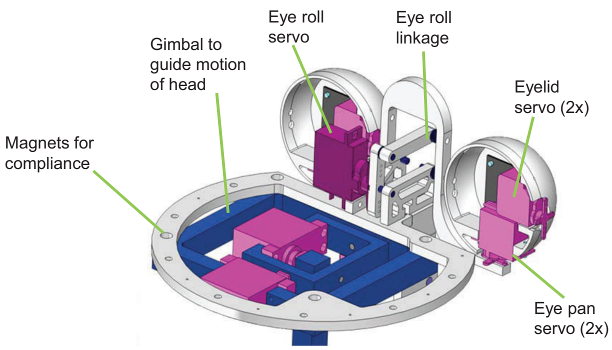

Fig. 4. The structure of the penguin's eyes. The robot has 3-DOF eye motion plus control of the eyelids. Each eye incorporates a camera in the pupil to provide stereo vision capabilities.

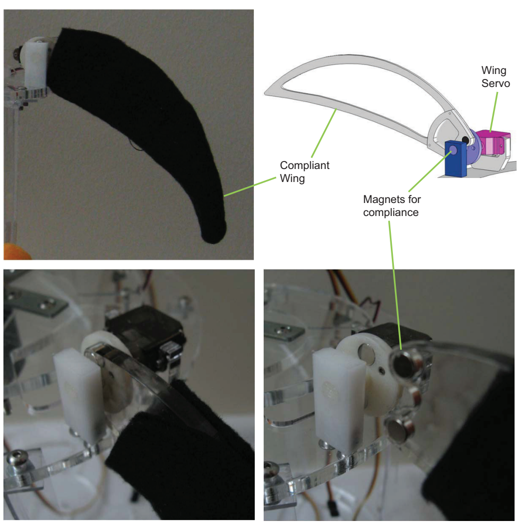

Fig. 5. The robot's independently controllable, compliant wings.

2) Feet, Beak, and Wings: The robot's appendages both give the penguin a more friendly cartoon-like appearance and also enhance the ability to present emotions and evoke responses from the children. Both of the penguin's wings can be independently controlled. The wings, being one of the most probable appendages to be pulled or twisted, were designed to withstand pulling and twisting in any direction. They are attached to the body by magnets, allowing them to be driven by a servo, but if they were pulled on, they would separate from the body with no damage to the servo. Most of the wing is made from thin polycarbonate, giving it compliance in all of the directions that the magnets do not as shown in Fig. 5.

The penguin's feet are soft, made of felt and batting as shown in Fig. 8. They can be played with by the child, and if they are squished, no harm comes to them. They are attached to the body of the penguin with Velcro, so when they are pulled on, they separate from the body of the penguin, causing no damage, and can be reattached easily. The beak is made of the same materials and with the same compliance as the feet, but the compliance is achieved with magnets and alignment pins rather than Velcro. When interacting with the child, beak motion may be coordinated with non-verbal sounds and utterances that the robot makes and it may also be controlled to help demonstrate the robot's emotional state.

C. Control System

The robot has two modes of operation: autonomous mode and teleoperation mode. In autonomous mode, the robot interacts with the child with no direct control by a clinician. It is able to observe the child's body motion and head movement, and the robot's head and eyes can move correspondingly. The wings and beak can also be used to generate interactive motion, and recorded sounds can be used to communicate emotion and render a playful environment. In teleoperation mode, a therapist (either at a remote site or with the child) could observe the child's behavior through stereo cameras and operate a joystick to control robot movement. Semi-autonomous control, such as face tracking, can still be utilized in this mode. In either mode, the robot can further be used as a diagnosis tool to record children's behavior including body motion, gaze direction and other parameters, and evaluate the treatment progress with qualitative metrics.

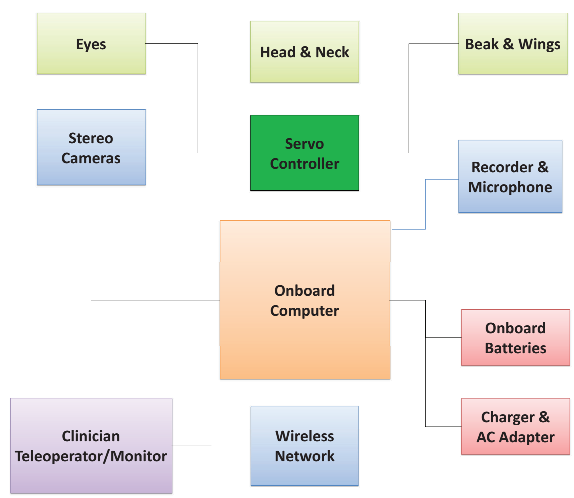

Fig. 6. Block diagram of the robot's system architecture.

1) Controller Hardware: An Intel Atom-based single board computer (SBC) serves as the robot's computational core. This computer has identical capabilities of a standard Netbook including the low power consumption. The SBC provides sufficient computational power for image processing and natively includes networking, data storage, and a USB interfaces to peripherals such as the the webcams, while maintaining a low cost. Two servo controller modules

(Pololu Corp., Las Vegas, Nevada) are used to interface the computer with the actuators, each can drive 8 servos from a single serial port. These servo controllers were chosen for their low cost and ease in adding additional DOF. The electronics are suspended with elastic cord such that they would avoid damage in a fall. The robot runs on the Ubuntu Linux operating system installed on a solid state hard drive. Since the device is intended as a research tool, a well defined Java API is provided to control the robot motions.

2) Software Interface: As the robot is intended to interact with children by active movement or to observe children's behavior during diagnosis, head pose and gaze direction estimate is a key factor to the humanoid robot operation. For head pose estimate, an appearance template method [13] is used to detect six facial features (four corners of eyes and two corners of mouth) by normalized correlation. 3D stereo matching is then performed to determine the Cartesian position of each feature. Head pose estimate (R, t) can be cast as optimization problem [13]

$$\arg\min_{R,t} \sum_{i=0}^{N-1} \omega_i (Rx_i + t - y_i)^T (Rx_i + t - y_i) \qquad (1)$$

where N is the number of features, x_i is the feature position vector in the 3D feature model and y_i is the position measurement of a feature acquired in the feature tracking and ω_i is the weighting factor obtained during feature tracking.

The algorithm is implemented with the software package FaceAPI® (Seeing Machines Limited, Australia). It allows highly robust and real-time face tracking and provides head position and orientation coordinates per frame of video. Head motion in $\pm 80°$ is allowed for successful detection. It is also robust to partial occlusions, illumination, skin color variation and glasses etc. Fig. 7 shows six head gaze tracking snapshots. The person moves their head up, down, left and right, while the head gaze coordinates are overlaid on the images for each head orientation. The software provides the position and alignment of the head coordinate frame which can be used in both face tracking for interaction and gaze tracking for diagnosis and monitoring.

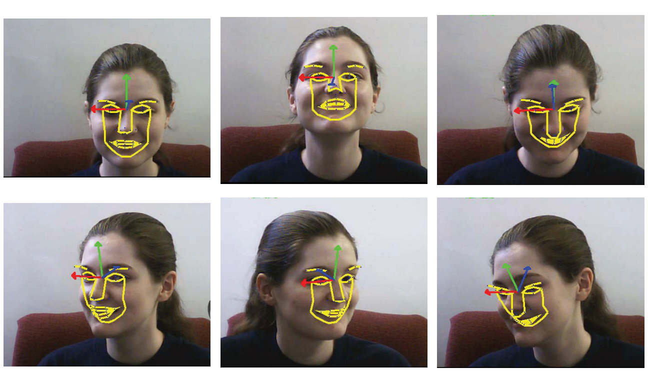

Fig. 7. A series of gaze tracking snapshots showing the head gaze coordinates for different head orientations. The software tracks the location and orientation of the child's head with respect to the cameras in the eyes, gaze direction can be inferred from the shown coordinate frame.

Fig. 8. PABI©: Penguin for Autism Behavioral Intervention

III. DISCUSSION

PABI has been designed as a research platform for robot-assisted therapy of children with autism. The robot has many applications after it has been fully developed; it will be able to be used to autonomously produce repeatable sounds and gestures and to record the response of the child for use in the diagnosis of autism. It will have a teleoperation mode such that a professional trained in the diagnosis of autism can sit and control it, using it as an interface. The robot will soon be capable of interacting autonomously with an autistic child. We intend to refine the control software and begin trials with the system in the very near future. After demonstrating and validating the concept, future iterations of the robot will have further refined designs including tougher materials such as Delrin and be designed for manufacturing in larger volumes.

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