B^{3}IA: A control architecture for autonomous robot-assisted behavior intervention for children with Autism Spectrum Disorders

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Abstract— **This paper describes a novel control architecture, B^{3}IA, designed to address the challenges of developing autonomous robot systems for use as behavior intervention tools for children with Autism Spectrum Disorders (ASD). Our goal is to create a system that can be easily adapted for use by non-roboticists engaged in ASD therapy. B^{3}IA is a behavior-based architecture for control of socially assistive robots using human-robot interaction in the ASD context. We hypothesize that the organization of a robot control architecture is important to the success of a robot-assisted intervention, because the success of such intervention hinges on the behavior of the robot. We detail the organization of B^{3}IA and present preliminary results from experiments that begin to experimentally test this hypothesis.**

I. INTRODUCTION

Children diagnosed with Autism Spectrum Disorders (ASD) have varying degrees of impairments in acquiring communication and social skills [37]. A prominent goal for ASD intervention is to motivate and reward the improved development of proactive social behavior and spontaneous experience sharing [29]. Consequently, active research is focused on developing intervention strategies that use caregiver and therapist behavior to provoke and encourage social behaviors in children with ASD [17]. Work to date has identified and developed engaging scenarios that motivate social behavior across the diverse spectrum of ASD.

The affinity of children with ASD to mechanical objects is well established [16]. Robots and computers have also been shown to have promise as potential therapeutic and assessment tools, because children with ASD express interest in interacting socially with such machines [15, 33, 38]. Due to its intrinsic value as an interesting and rewarding entity, a robot or a computer character can become a focus for shared attention and interaction with a teacher, parent, or peer. Both computer-based virtual environments [30] and embodied robots [8] have been proposed for facilitating social interactions.

Understanding what features of the robot's appearance and behavior are responsible for engaging children is critical. Currently, it is not yet clear whether the behavior of the robot is the elicitor of the observed social benefits, or if it is some other feature of the system. We hypothesize that the behavior of the robot is largely responsible for provoking and encouraging social behavior in children with ASD. If data support this hypothesis, then the architecture that defines the behavior of the robot in interactive settings becomes very important. It is toward that end that we have developed a novel robot control architecture with the specific purpose of being used in the ASD intervention context.

The core challenges involved in using robots as social tools for ASD intervention include sensing and interpreting the user's activities and social behavior, monitoring the dynamics of the current social situation, and selecting and producing appropriate robot behavior. While each of these problems has been approached in whole or in part for non-ASD robot users, there has been little success in making an autonomous system for use as an augmentation of traditional therapeutic behavior intervention for ASD. This paper presents preliminary data that supports the hypothesis that the robot's behavior has a strong effect on a child's social behavior. This paper describes a novel architecture, Behavior-Based Behavior Intervention Architecture (B^{3}IA), specifically designed for use in robot-augmented behavior intervention for children with ASD.

II. BACKGROUND AND RELATED WORK

ASD are a group of life-long pervasive developmental disorders [21]. The degree of their severity varies greatly across the spectrum, ranging from severe socio-communicative impairments to near-typical social functioning. The common age at diagnosis is between 24 and 36 months. Children with ASD exhibit chronic and robust deficits in social and communication skills [37] going beyond delays in language development In addition, individuals with ASD have an impaired ability for imitation [32], imaginative play, and non-verbal communication. Early intervention is critical for enabling a positive long-term outcome, and even so, many individuals need high levels of support and care throughout their lives.

Robotics and computer agent research already shows great promise for use in a range of application domains, including ASD diagnosis and intervention [3, 19, 26, 31, 33]. Assistive robotics is also being studied as a tool for ASD diagnosis and socialization intervention. The larger goal of the work we describe is to provide a general, principled, and validated methodology to facilitate the development of such systems.

A. Socially Assistive Robotics and ASD

Human-robot interaction (HRI) is aimed at a range of problem domains and applications, ranging from tasks too dangerous for humans, such as bomb detection and other military support tasks [7], to those easier for a robot to do, such as multi-modal sensing and exploration [34], to theoretical explorations about what the roles of robots in society are and what they should be [11].

Socially assistive robotics (SAR) is a growing area of research within HRI that develops robot systems for elder care, education, people with social and cognitive disorders, and rehabilitation, among others. SAR is the intersection of Assistive Robotics, which focuses on robots whose primary goal is assistance, and Socially Interactive Robotics [12], which addresses robots whose primary feature is social and not physical interaction [9]. SAR arose out of the large and growing body of applications suitable for robot assistance that involves social rather than physical interaction. SAR is a domain of HRI, in that social assistance through robotics is facilitated by human-robot interaction.

As noted above, robots have been shown to be a promising tool for ASD intervention. Kerr et al. [18] emphasize the importance of scaffolding in the virtual system design to facilitate social skill instruction; a virtual system was used by Tartaro and Cassell [36] to create authorable characters for developing social interactions with high functioning ASD children in story telling scenarios. Similarly, mounting evidence [33, 38] shows that ASD children that are otherwise asocial display social responses and engage in social interactions with robots. A simple robot was shown to have a positive effect on gaze and physical contact behavior when acting as a social mediator [19, 27]. The European AURORA project [8] uses simple mobile robots that incorporate key aspects of human communication and interaction such as eye gaze and turn taking to help guide a child with autism toward complex social interactions. They envision using a robot as social mediator, first exhibiting a small set of behaviors, widening that range of interactions over time [8]. Results have shown that ASD children proactively interact with simple robots and that such robots can mediate joint attention [31]. Finally, storytelling robots have been used for social skill instruction for children with ASD [20].

B. Robot Architectures

Control architectures provide guiding principles for robot system organization and implementation. The architecture we introduce is behavior-based [23]. This section briefly overviews the background on behavior-based control principles and relevant other HRI architectures.

It can be important to ground robot architectures in real-world interactions and enabling real-time response through distributed system organization [6]. Behavior-based control (BBC) and architectures for BBC [5] are based on that philosophy. BBC structures the control system as a collection of concurrently executing task-achieving modules called behaviors, which take inputs from sensors and/or other behaviors and send outputs to actuators and/or other behaviors in the system. Unlike reactive control, BBC has the same expressive power as hybrid robot control methods, enabling planning and learning in addition to real-time control [23, 24, 25].

Research in HRI has stimulated the developed of novel control architectures. Breazeal [4] and Arkin et al. [1] implemented drive-based approaches which observed human actions and, in concert with a robot's own motivations, made decisions regarding behavior. Our approach contributes a novel component by storing and examining the history of HRI over time, rather than only utilizing recent behavior to select actions. Baek et al. [2] used an interactive approach that relates to ours. It is based on a timeline of the user's actions which serves as a basis for anticipating when the user may require a particular action to be performed by a robot. The architecture tracks user behavior over time, but unlike our approach, does not record it. The timeline is used to learn a user's pattern of behavior, not to observe interaction. In contrast, Goldberg and Matarić [13] tracked robot behavior over time enabling the robot to learn a self-model, but did not involve user interaction. Our approach combines explicit tracking of user and robot behavior as a means of measuring social behavior, and action selection.

III. IMPLEMENTATION DETAILS

Our experimental test-beds for a robot-augmented intervention are shown in Figure 1. The different experimental configurations use the following components:

Pioneer 2DX mobile base (Figure 1, left) that can move forward, backward, and turn. It can be equipped with cameras, laser range sensors, and speakers, along with other task-specific sensors and/or actuators.

An upper-torso humanoid (Figure 1, middle) with 19 DOF, including two 6 DOF arms, a pan-tilt neck, and an expressive face. This robot was designed for mobile, low-power, safe social interaction and uses motors that apply no harmful force. The robot can run for up to a 90-minute session. It is typically used mounted on the mobile base.

Large, brightly-colored buttons (Figure 1, right) are installed on top of the mobile base. The brightly-colored discs serve multiple purposes: they aid overhead vision tracking of the robot base and are appealing to children as a visual and tactile interface to trigger robot behavior.

A computer-controlled bubble-blower (Figure 1, right) is mounted on the front of the mobile base, for use with bubble play. It can be activated randomly, or in response to sensor input for the robot (such as vocalizations, button-pushes, or when the user approaches).

Speech generation using an on-board speaker based on the AT&T text-to-speech system allows us to synthesize human- or computer-sounding speech for use in expressive vocalization. The speech can be synchronized with the mouth movements on the humanoid head.

We have also developed the following sensors specifically for observing interactive behavior:

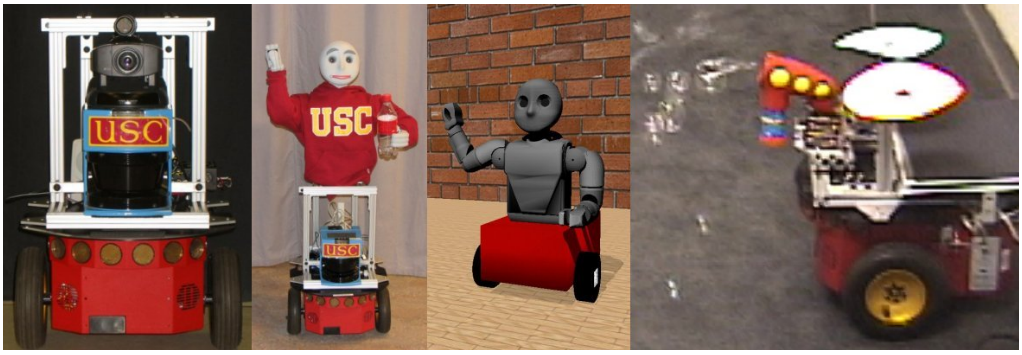

Fig. 1. Experimental test-beds. Leftmost: Non biomimetic mobile robot. Left-middle: Biomimetic anthropomorphic humanoid torso mounted on the same mobile robot base. Right-Middle: Simulated humanoid torso and mobile robot base. Rightmost: Bubble blowing setup on the mobile base.

Overhead position tracking: Previous work [10] has shown that planar position tracking can infer information about social intentions. This information included whether a user wished to interact with a particular robot and whether the user was interacting with another person. While the robot's interaction with the user involves attempting social body orientation (i.e., facing the child), when the child moves away (to talk to parents, be left alone, etc.) the overhead camera is employed to track the user so the robot does not lose track or move about searching. The system has been validated in the lab.

Wearable motion capture: Typically, motion capture is accomplished by instrumenting the user with a number of visual fiducials and using cameras located in the environment to track their positions. This approach, however, is not scalable to low-cost, real-time uses in uninstrumented environments. We developed an inertial measurement unit (IMU) based motion capture system with light-weight wearable sensors that provide real-time pose and gesture information [28]. The system was effectively used to track stroke patient movements [22]; we have made modification for its use with children with ASD, in order to address skin sensitivities. In the context of ASD research, we will use these sensors for the imitation scenarios, such a Simon-says game where the robot initiates a gesture and encourages the child to imitate them. The robot can monitor the pose of the child, and determine if the child is imitating the robot, or use the pose data to imitate the child.

IV. EXPERIMENTAL VALIDATION

As stated in Section I, we hypothesize that the behavior of the robot has a significant influence on the social behavior of the child interacting with it. To gather data to test this hypothesis, we collected video data from a small pilot experiment of children interacting with a bubble-blowing robot. Our experiment was a sequence of presentations of a robot that blows bubbles when the child pushes a button on the robot (see Figure 1). We allowed open-ended interaction during the experiment, giving the child complete freedom to move about the experimental room. A family member of the participant was present in the experimental area.

We created two variations of this scenario. In the first, called the contingent condition, the robot blows bubbles when the buttons are pushed. In the second, called the random condition, the robot blows bubbles at random intervals. Each child experienced both scenarios in a randomized order. In total we recruited four children (3 male, 1 female; 3 with autism, 1 typically developing; mean age 7.75 years old). One could not participate fully in the experiment due to a malfunctioning bubble blower.

We observed that the children behaved remarkably differently in the two conditions. One child would actively engage the robot during the contingent condition (and also interact proactively with his parent), but would just sit back and not interact with anyone during the random condition until the robot would blow bubbles, then he would move to pop them and lean against the wall. Similar behavior was consistently observed from for all three children.

These results support the hypothesis that the behavior of the robot affects the behavior of a child with ASD. Another interesting observation is that robot speech was unsettling to two children, while it was encouraging to one. In addition, we observed that the movement of the robot encouraged the children to move, while they tended to be still when the robot was not itself moving. To better understand which social behaviors are affected, we are in the process of conducting a larger quantitative study based on this experimental design.

V. ARCHITECTURE DESIGN

Based on the encouraging pilot results described above, we developed a robot control architecture that can be personalized to address the specific needs of ASD intervention. The Behavior-Based Behavior Intervention Architecture (B^3IA) is part of a larger research program in our group that aims to create a methodology, approach, architecture, and supporting algorithms for HRI-based intervention and to evaluate the results in the context of ASD.

There are a number of requirements, summarized in Section V-A, that are specific to behavioral intervention and must be taken into account in designing the architecture. These are best illustrated, as well as validated, in the context of experimental scenarios. We developed specific experimental scenarios, based on DIR/Floortime therapy, which will be used for evaluating the architecture.

A. Role of the Robot

DIR/Floortime therapy (DIR: Developmental, Individual-Difference, Relationship-Based) is a flexible, individualized

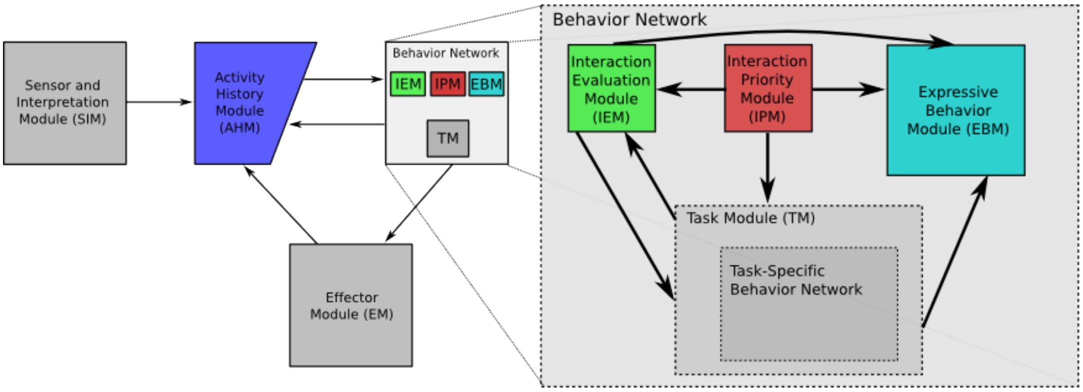

Fig. 2. A schematic of the control architecture and the behavior network

intervention approach designed for intervention with children with autism, which involves a human therapist using the child's existing social behavior to build new social behavior and increase circles of communication [14]. DIR/Floortime therapy can involve the use of other people known to the child as well as other objects, such as toys, in order to create social situations. The use of other people or toys during a DIR/Floortime session allows for the easy addition of a robot in place of a toy as part of the therapy process.

In this context, the robot acts as a catalyst for social interaction, and a conduit for social behavior. The larger goal of the robot is to promote more interaction with both human and robot. A robot-assisted intervention system must meet the following requirements in this intervention context:

1) Sense the user's actions and understand his/her approximate meaning in the given social context;
2) Act autonomously for designated interaction scenarios;
3) React not merely to the immediately sensed situation but also to the interplay of interactions over time;
4) Evaluate the quality of human-robot interaction over a specified period of time.
5) Alter its behavior based on user-specific parameters. These parameters should be set from a human-readable interface.

B. *Sensing, Decision, and Action*

In behavior-based architectures, sensor data are processed by the behavior network, which controls the effectors. B^{3}IA is designed to work within that framework. The Sensor and Interpreter Module (SIM) controls how the robot observes the behavior of humans and objects in the environment. For example, audio data are captured, and the constituent speech and non-speech vocalizations information analyzed. The user's position is observed over time to determine relevant elements of the social use of space (e.g., whether the child is approaching the robot while being addressed by it). The SIM manages multi-modal data from a variety of task-specific sensors, and passes it on to the Task Module.

The Task Module (TM) is a behavior network wherein most of the operational decisions regarding the robot's behavior are made. In B^{3}IA, this module is where most of the task- or scenario-specific control occurs. The network consists of a combination of behaviors necessary and specific for the robot to operate safely in a given scenario (for example, for a ball-passing game, a behavior to kick the ball to the child) and behaviors generic to social interaction (a behavior to maintain a safe and social distance between the child and robot).

The Effector Module (EM) is responsible for the operation of the physical hardware, designed to accommodate a broad range of effectors (wheels, arms, facial motors). The EM processes actuator commands in parallel, allowing for simultaneous control of multiple effectors. Action selection is done in two parts. First, task-level action selection is done by the TM as described above, and social action selection (behaviors related to facial expressions and gestures, social use of space, etc.) is handled by the Expression Behavior Module (EBM). Second, arbitration between actuation of social behavior and task-oriented behavior is handled by the EM.

C. *Activity History Module (AHM)*

Human-human and human-robot interaction are not instantaneous events. However, the nature of sensors and sensor processing lends itself to processing immediate data rather than activity data over time. To enable algorithms utilizing time-extended HRI, in B^{3}IA all interpreted sensor data, along with interpretations of ongoing user and robot (self) behaviors, are stored in a time-indexed form in the Activity History Module (AHM). Robot actions are also stored in the AHM (Figure 2). Processing both immediate sensor data, and data over a period of time, have been implemented in past systems. This type of behavior history and evaluation is unique in that both the human actions and the robot's actions are stored in a single place. The analysis of the interaction (done by the Interaction Evaluation Module, Section V-D) is used to evaluate the quality of that interaction, which can be used as a parameter for the robot's behavior.

The purpose of the AHM is to collect data and store it in a form resembling human annotation of social interaction. Examples of this data include vocalizations (including recognized content of speech utterances), movement actions (the child moves toward/away from robot/parent), gestures, button-presses, and other interactions with the robot. The goal is to be able to analyze this information in the same fashion as human annotation of video recordings can be analyzed.

Our implementation of the activity history uses a MySQL database stored on or off of the robot, accessible over a wireless network. Processing a period of time will be implemented as SQL queries of the database. Real-time (and off-line) analysis of the user-robot interaction is facilitated by having the user's and the robot's actions are stored in joint, time-coded fashion.

D. Interaction Evaluation Module (IEM)

Effective HRI over a period of tens of minutes to an hour or longer requires an ongoing evaluation of the interaction goals and progress. Methods for automatic evaluation of ongoing interaction have been proposed by Tardif et al. [35]. Our architecture uses those ideas, by applying the data from the Activity History Module as input to the Interaction Evaluation Module (IEM). Using that history, as well Tardif's technique for quantitatively evaluating the quality of interaction for children with autism, the robot can evaluate how much interaction is currently occurring as well as how rich that interaction is.

The IEM queries the MySQL database that stores the AHM. For a few windows of time (tentatively 10 seconds, 30 seconds, and 1 minute) a selection of the AHM will be queried. The data will be processed for a number of features, including the number of social behaviors observed, and the rate of observed behavior. More advanced analysis includes determining the depth of interaction (the number of back-and-forth interactions) in a given time-period. The depth of interaction for a given range of time will be used as a measure of the quality of interaction during that range of time. While identifying related interaction will be difficult to accomplish automatically, it will be done by human coders after the fact.

E. Interaction Priority Module (IPM)

The Interaction Priority Module (IPM) allows for a human operator to set interaction priorities for the intervention interaction. This input is designed to be minimal, consisting of session-level behavior priorities, not direct tele-operation. The results in Section IV demonstrate the need for personalization. For example, if a child has particularly acute issues with turn-taking in conversation, encouragement of such behavior could be prioritized higher than other activities. An intervention can be personalized to a child's needs through simple initial input. At the implementation level, the initializing input provides prioritizing bias for the behavior selection mechanism.

This module is motivated by behavior intervention therapies; in the context of typical intervention, a therapist modulates his/her behavior and tasks in order to observe individual behaviors that are relevant to the diagnosis and therapy of ASD. In B^3IA, the interaction priority module allows a human operator to similarly select what activities and behaviors the robot should emphasize. This module is important for future deployment of robot-assisted intervention in clinic or home settings as it enables therapists and family members to design a personalized style of interaction. The output from the IPM feeds into the task-specific behavior module to assist in behavior arbitration and action selection.

We will implement the IPM by determining which robot behavior best provokes particular social behavior. Once these correlations have been established, we will create a human-readable menu of social behavior that can be prioritized. A human operator can then select a particular social behavior. The IPM will then prioritize the corresponding robot behavior.

F. Expression Behavior Module (EBM)

This module contains behaviors dedicated to the robot's affect generation. Affect includes the projected emotions, personality, expression (facial or gesture), and direction of the robot's overt attention. Using effectors such as the mobile base, speech, and the humanoid arms and face (or the mobile robot's pan-tilt-zoom camera movement), the robot is able to express social behavior through affect.

Affect is used in two ways by the EBM. First, the affect of the robot changes to reflect its internal state, dependent on the interaction scenario being executed and on the state of social interaction. Second, the affect of the robot changes based on the therapeutic feedback the robot aims to express (i.e., encouragement or discouragement). For example, the robot smiles and expresses positive emotions when it observes that the interaction is going well, and less so when the interaction is going poorly. The robot expresses negative affect when the child is doing the opposite of what the robot is suggesting. While children with ASD are not likely to interpret the artificial affect in a manner similar to that of typically developing children, the goal of using human-like affect is to intentionally attempt to accustom ASD children to human-human interaction through analogous HRI. This is the underlying philosophy of using the robot as a social conduit; toward that end we use platforms whose size, form, and behavior resemble people more than toys.

VI. SUMMARY AND FUTURE WORK

This paper presented an approach and a supporting robot control architecture for a autonomous robot-assisted intervention for children with ASD. We briefly described a motivating pilot experiment that demonstrated that the behavior of the robot affects the social behavior of a child with ASD.

The proposed B^3IA uses specialized modules for activity modeling and history capture to monitor the status and quality of social interaction between the robot and the user. The structure of B^3IA is made as general as possible for reuse across a variety of intervention tasks and scenarios. The unique elements of B^3IA were created to address the challenges inherent in designing autonomous robots for ASD intervention. However, these elements could readily be applied to other HRI systems that require time-extended interaction.

Future work involves implementing the interaction priority module (IPM) and the expression behavior module (EBM) and testing their effectiveness. Critical to the success of the IPM is identifying behavior of the robot that provokes particular social behavior for children with ASD and providing a human-understandable interface for prioritizing that behavior in order to personalize an intervention.

Finally, we will continue to develop and evaluate the AHM and IEM to provide measures of quality and quantity of interaction behavior. This development will involve tailoring the IEM to match human ratings of social interaction. We will test the effectiveness by using interaction quality as a parameter for an intervention. We will test these architecture features in upcoming repeated-measures studies as well as intervention studies with a large cohort of children with ASD.

ACKNOWLEDGMENTS

The authors thank Dr. Clara Lajonchere and the Autism Genetic Resource Exchange staff. We also thank Prof. Peter Mundy for expertise with ASD assessment and intervention. This work is supported by the Nancy Lurie Marks Family Foundation, the Okawa Foundation, and a NSF Computing Research Infrastructure Grant.

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