Perspectives on Mobile Robots as Tools for Child Development and Pediatric Rehabilitation

Abstract

Mobile robots, i.e., robots capable of translational movements, can be designed to become interesting tools for child development studies and pediatric rehabilitation. In this paper, we present two of our projects which involve mobile robots interacting with children: one is a spherical robot deployed in a variety of contexts, the other being mobile robots used as pedagogical tools for children with pervasive developmental disorders. Locomotion capability appears to be key in creating meaningful and sustained interactions with children: intentional and purposeful motion is an implicit appealing factor in obtaining children's attention and engaging them in interaction and learning. Both of these projects started with robotic objectives, but reveal to be rich sources of interdisciplinary collaborations in the field of assistive technology. This paper presents perspectives on how mobile robots can be designed to address the requirements of child-robot interactions and studies. It also argues that mobile robot technology can be a useful tool in rehabilitation engineering, reaching its full potential through strong collaborations between roboticists and pediatric specialists.

Keywords: Mobile robots, Infant-robot interaction, Untrained users, Locomotion, Adaptation, Intelligent Systems.

INTRODUCTION

Systems can be loosely qualified as intelligent when they have the ability to perceive, reason, act in the world and interact with humans. Designing and developing intelligent systems entails creating artifacts, such as robots, that emulate the human ability to perceive, to reason, to make decisions, and to act in complex environments or situations. Robots, and more specifically mobile robots that are able to move in real life settings, are certainly great examples of intelligent systems. Robots working in human populated environments must successfully negotiate three issues: manipulation, navigation and communication. Manipulation is required when robots must interact with a material form in some way, for example, manipulating a cup for a child in a wheelchair (Cook *et al.* 2002). Navigation involves using locomotion capabilities coupled with sensory information which, when combined together, enable the robot to move and navigate its current environment. Communication allows robots to interact with people. The intelligence of such systems manifests itself through the appropriate integration of structural components, on-board energy source, sensors, computers, programming and actuators, arranged so that they can effectively deal with the intended operating conditions. As a result, mobile robotic design is a highly challenging endeavor, even more so when the robots must interact with children.

Robotic devices that assist humans come in many shapes and forms. Most of the recent work in rehabilitation robotics is aimed at the assistance of human movements (e.g., intelligent wheelchairs, manipulators and robotic arms mounted on wheelchairs (Bien & Stephanov 2004), and guidance systems for the visually impaired (Kulyukin, Gharpure, & Nicholson 2005) or the elderly (Pollack *et al.* 2002)). Robotic assistive technology for children is itself a growing area of research (Besio 2002; Dautenhahn & Werry 2002; Robins *et al.* 2004a; 2004b; Kozima & Yano 2001; Michaud & Theberge-Turmel 2002; Michaud, Duquette, & Nadeau 2003; Plaisant *et al.* 2000) and could prove fundamental for children with all kinds of disabilities. It has been found that children are often attracted to robotic devices (Woods, Dautenhahn, & Schulz 2004), and such technology may enable children with physical disabilities to play and facilitate learning in those who have cognitive challenges.

Our interest lies in the custom design of mobile robots that interact with children as their primary goal. By moving intentionally and purposefully in the world, mobile robots can create diverse situations in which a multitude of different interactions can take place. The greater the freedom of movement a robot has, the more diverse and ultimately interesting its participation within a social environment will be. We believe that this freedom of movement engages and sustains the attention of children which, through the diversity of situations, may potentially help them develop new skills, learn (Barclay *et al.* 1975) and possibly generalize. When designing these robots according to specific experimentation or application criterion, it is also possible to consider the robot's appearance and communication through a variety of channels (sounds, voice, lights, movement) which can influence interactions with a child. It appears that motion and form can independently contribute to interaction[1] : based on the experiments by Heider and Simmel (Heider & Simmel 1944), motion by itself is thought to be sufficient to create complex social attributions. Draper and Clayton (Draper & Clayton 1992) showed that children paid more attention to a live teacher and to a moving robot giving them instructions, compared to a stationary robot. No significant difference between the human teacher and the mobile robot was observed. Kahn et al. (Kahn *et al.* 2004) also demonstrated that children differ in their behavioral interactions between a robotic dog and a stuffed dog.

Research on human-robot interactions involves a great variety of design configurations, as reviewed in (Fong, Nourbakhsh, & Dautenhahn 2003). Locomotion capabilities within these works are normally either very limited or obtained from general purpose robotic platforms which are usually expensive and complex. Both locomotion and the custom design of robots for a pediatric environment bring about important challenges, especially when considering the following requirements: *Robustness* – the ability to withstand rough and diverse interplay situations; *Safety* – not to harm the child, which also means that the weight and the strength of the robot should be carefully considered; *Simplicity* – so that the user can easily understand how to interact with the robot; and *Cost* – to make this emerging technology financially accessible to the pediatric domain. We believe that effectively combining these factors requires interdisciplinary work with roboticists

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[1] According to personal communication with Frank Pollick, Department of Psychology, University of Glasgow, November 2004.

and pediatric specialists to initially derive design specifications, and then to conduct the evaluation of such designs, ultimately leading to the development of superior robots.

This paper presents an overview of works carried out since 1999, when the idea of designing custom-made mobile robots to study child development within the pediatric domain was emerging. The first project discussed involves a spherical robot used to study, among other things, the impact of autonomous motion of a robot on infants. The second is a project that investigates the effects of various robots on children with pervasive developmental disorders (PDD). Both projects involve human-robot interaction studies with untrained users (in our case children and infants). Research results for these projects are reported in the referenced works, and their methodologies, hypotheses and analyses are not specifically presented here. The purpose of this paper is to outline and discuss perspectives coming from these projects. Designing and building robots that can effectively function within these complex domains involves refining design specifications through an iterative process of different experiments. We describe how these projects were initiated and how they evolved, focusing more on the underlying design issues, the types of trials conducted, along with general conclusions derived from these trials. Two projects were initiated with robotic incentives, aiming primarily at proof-of-concept case studies to observe how the technology can be beneficial in such pediatric applications. These projects gradually evolved into interdisciplinary collaborations. Roboticists benefit from these collaborations by being able to improve the design of the robots. Also, the scientists and therapists involved learn about the possibilities these new technologies have to offer. Combining different areas of expertise creates new research opportunities, and collaborations are essential for such technologies to reach their full potential. By presenting our perspectives regarding the design and the evaluation of mobile robots in pediatric applications, we hope that this may help generate ideas and encourage new initiatives involving strong collaborations between roboticists and pediatric specialists.

2. Roball, the Spherical Robot

The Roball project started from the perspective of building a robot that cannot be flipped over. One simple and inexpensive solution is to encapsulate a robot inside a sphere, and to use the sphere to make the robot move around in the environment. It was later that the many benefits pertaining from applying such a robotic system to the domain of children were realized. As children are often physically aggressive with toys, a robotic toy cannot be designed with the expectation that children will play with it in a manner that we find appropriate. Therefore encapsulating the robot inside a shell helps protect the fragile electronics (sensors, actuators, processing elements), thus making it robust and ideal for interaction with children. Additional benefits from using a spherical ball is the motion and movement provided by the shape. This allows for easy navigation in cluttered playrooms. Another aspect is that children are frequently exposed to ball-shaped toys early in life. Therefore, with all these factors in mind, the goal evolved into the design a spherical autonomous mobile robot that can generate various interplay situations with children in playroom environments. Contrary to current robotic toys, our objective with Roball was not to create the illusion that Roball was an entity that needs caring and nurturing. Other toys may be more appropriate for this application due to their appearance which encourages such responses. We preferred to generate interactions with Roball that were in direct relation to its dynamics and structure.

2.1 Roball-1: The Proof-of-Concept

Our first prototype of Roball, built in 1998, is shown in Figure 1. It is 6 inches in diameter and weighs about 4 pounds. This prototype is made of a plastic sphere (it is in fact a hamster exercise ball) constructed from two halves that are attached to each other, a Motorola 68HC11 microcontroller board, a ISD ChipCorder device allowing the generation of pre-recorded messages and sounds, tilt sensors, one servo-motor and two DC motors. These two motors are attached to the extremities of the spherical shell. Turning in the same direction, they move the center of gravity of the internal plateau forward or backward, for longitudinal robot motions. Motor speed is regulated according to longitudinal inclination of the internal plateau, keeping the robot's center of gravity close to the ground. Steering is achieved using the battery as a counterweight mounted on a servo-motor, making the robot go straight or tilt on one side or the other as the shell rolls. Tilt sensors are used to provide inclination measures for longitudinal inclination and for lateral (left and right) inclination. The overall cost is less than 150 $CAD in materials, using off-the-shelf components. This first prototype proved to be sufficient for the proof-of-concept.

Using this platform, we programmed the robot to generate interplay situations with children through the use of motion. Roball's programmed behavior generates two-phase cycles: the robot wanders around in the environment, moving away from obstacles sensed with the horizontal tilt sensors, for approximately 60 seconds; then Roball stops moving for a period of time between 30 to 60 seconds, determined randomly. While stopped, Roball randomly selects one of three actions: through pre-recorded vocal messages, Roball asks to be spun, to be shaken or to receive a small push to start moving again. If spun, Roball can indicate that it feels dizzy or wants to be spun again, depending on the duration of the spin. During spinning, a message expressing excitement is generated. If the child responds with the correct action to a request (spinning, shaking or pushing), then Roball thanks the child. However, if the child does not interact the way requested by Roball, the robot will ask the child to stop. All these responses are detected using the onboard tilt sensors: spinning is recognized when the left and right tilt sensors are both activated, a state occurring only when the robot is spinning in place; shaking is detected as rapid changes in the horizontal and vertical tilt sensor readings occur; pushing is sensed by the horizontal tilt sensors. If Roball does not perceive any interaction from the child, it will indicate that it is getting bored. After a predetermined length of time has passed, in which Roball has received no interaction, or after the child gives Roball a small push as a response to a pushing request, Roball continues to wander around in the environment.

2.1.1 Objective of the Case Studies

Purposeful movement is something not frequently observed in low cost toys: they are usually teleoperated or move in a fixed direction often dictated by the child. The objective was therefore to see how autonomous navigation by a toy could create interesting new interactions with children. Since the sphere in the first prototype of Roball was not robust enough to handle prolonged or intense interplay situations, our initial intention was simply to study, from a robotic point of view and through simple case studies, how Roball could create interesting interplay situations with children in various environmental conditions.

Fig. 1. First prototype of Roball.

Fig. 2. Subject3 playing with Roball (left); Subject4 at 10 months old playing with Roball (right).

2.1.2 Trials

We conducted a series of trials (Michaud & Caron 2000) with Roball and a convenience sample of four boys: two typically developing 3 year old boys (Subject1 and Subject2), a 11 year old boy with PDD (Subject3), and one typically developing boy (Subject4) who regularly interacted with Roball from the age of 10 months to 30 months. During the trials the children were allowed to play with the robot as long as and in any way they wished, except if the actions may have damaged the robot. The trials were conducted in natural living environments.

A variety of interactions were observed from the different children during these trials.

Subject1 was very active in his play with Roball, following the robot around everywhere it went (under tables, around the furniture), throwing a basketball to Roball, talking back to the robot when it produced vocal messages, asking questions regarding what the robot was saying. Subject2's play with Roball was different: he initially began by looking at it from a distance and smiling. He appeared to be intrigued by the fact that Roball was moving and talking on its own without having to be teleoperated (like his remote controlled car). The interactions Subject2 had with Roball were very gentle, letting the robot pass under his legs, acting on the requests made by the robot and repeating what the robot said. Subject3, on the other hand, did not listen to Roball's requests. While Roball was not moving, he played with it by making it roll on the floor between his arms, as shown on the left side of Figure 2, and by bringing the robot to his mouth, not looking at the robot: this is a typical behavior for children with PDD. This changed when Roball started to move again on its own: Subject3 stopped moving, kept looking at the robot, stood up, started to clap his hands and laugh. This showed that by moving, Roball encouraged and further engaged the child's interest. Finally, Subject4 at 10 months was just beginning to crawl and to stand unaided. He was instantly interested in Roball (shown right in Figure 2), catching and grabbing the robot as it changed behavior according to its activity modes. Subject4 did not seem to get tried of attempting to catch Roball or from simply watching Roball move: after 30 minutes we decided to end the trial, which upset Subject4. The positive responses, interactions and interest that were observed when Subject4 interacted with Roball were not so evident when he interacted with a basketball and a small train that could move in a fixed direction on the floor. Strong interest was again evident in Subject4 toward Roball at 14 months, 21 months and 30 months of age. During these later trials, Subject4 understood better what the robot was saying and interacted with it accordingly. Subject4 was also observed talking to Roball, explaining to the robot the different things happening in his life. Again this was not so evident in his behavior toward other toys.

2.1.3 Observations

During these initial studies, we observed many different effects generated by the purposeful movements of Roball. Varying interplay situations emerged from the interactions

TABLE I

Roball's Potential Use in Child Development

Skill	6-12	12-18	18-24
Motor	Following the robot. Visual tracking.	Precise manipulation (e.g., spinning).	Improving balance when grabbing a moving object.
Intellectual	Continued existence of moving objects.	Trajectories.	Respond to request. Symbolic games.
Social	Intermediate in parent-child interaction.	Attention on robot rather than on others.	Sharing. Imitating others.
Affective	Familiarization.	Self-esteem from parental encouragements.	Joy from responding correctly to requests.
Language	Recognize voice and reinforcements (e.g., yes, no).	Understand simple words.	Repeat what the robot says and does.

with different children, all with apparent enjoyment and positive interest toward Roball. Therefore, despite experimental results obtained in this first phase being anecdotal, they did confirm that purposeful movements of Roball, such as its ability to get out of difficult situations, its physical structure and its locomotion dynamics can lead to interesting games and interactions with children. These interactions were influenced by environmental settings and the child's character.

2.2 Roball-2: The Toy Prototype

Findings from Roball-1 justified the design of an improved prototype, named Roball-2. From discussions with child development experts, we identified that Roball should be used with infants from 6 to 24 months old, and that Roball prospectively could be used as a tool to validate different hypotheses on the development of motor, intellectual, social, affective and language skills with infants or children. At this age, mobility is a more predominant factor in interplay situations, before they start engaging in role playing games. Table I summarizes the potential uses of Roball in child development (Laplante 2004).

Shown in Figure 3, Roball-2 was designed to be a toy and was intended to be manufactured using thermoforming technologies. However, for validation purposes, the prototype was produced using Rapid Prototyping in ABS plastic (acrylonitrile-butadiene-styrene

Fig. 3. Second prototype of Roball.

copolymers). This made the shell thicker, heavier (also making the robot slower) and although more robust than Roball-1, it was not as robust as it would have been if produced with thermoplastic manufacturing. The shell was painted with bright colors and one side was made into a simple face with LEDs, a microphone, infrared sensors and push buttons for increased interaction capabilities. The internal mechanism was also improved to allow the robot to orient its face upward and to rotate on the spot. Four standard type C batteries were used for the internal counterweight and power, with easy access to replace them whenever required.

2.2.1 Objectives of the Case Study

We formulated two hypothesis to be validated by a series of trials: (1) Roball's intentional self-propelled motion should increase the level of attention of the child toward the robot, and (2) playing with Roball will increase the mobility of the infant.

2.2.2 Trials

Following the guidance and advice from child development experts we set up an experimental protocol attempting to separate mobility from the other the influencing factors (e.g., sound and visual effects, appearance, behavioral responses) making the child interact with the robot. The experimental protocol is based on individual case evaluation typically referred to as a A-B / B-A experimental protocol (Ladouceur & Begin 1980). Roball was presented to the child in different modes: A) Roball set to interact through the use of lights and vocal messages but without moving for 120 seconds; B) Roball moves autonomously in the environment for 60 seconds, then stops and interacts without moving for 60 seconds. Observations in mode A were intended to serve as the baseline for comparison with those of mode B.

The participants were six girls and two boys all typically developing and aged between 12 months to 18 months old. These trials were conducted at the children's kindergarten school, in a large room where the children did not usually play. Before beginning the trials, some time was allowed for the infants to become familiar with the presence of the robot, the environment and also that of the experimenter. Roball was presented to each child on two separate days. In day one, Roball executed mode A and then mode B. In day two, Roball started in mode B and followed with mode A. Interactions were videotaped and analyzed afterwards. Similar to Dautenhahn and Werry (Dautenhahn & Werry 2002) and Robins *et al.* (Robins *et al.* 2004a), we applied a second by second analysis technique to measure the amount of time the child was: 1) looking directly at the robot; 2) making physical contact with the child; and 3) moving toward the robot.

2.2.3 Observations

Results of these experiments are presented in detail in Michaud *et al.* (Michaud *et al.* 2005a). Experimenting with infants of less than 24 months of age proved to be a very difficult task, and probably even more because they were conducted by roboticists untrained in human studies. Inconclusive results from the quantitative evaluation were observed. These results may be due to a lack of regular exposure to the robot and explicit prompting by an educator (Robins *et al.* 2004a). No significant differences were observed between the two modes. Many factors may have influenced the results. Conducting experiments on only two days and for such short durations made the results sensitive to the mood of the children. Also, the interest from the individual children towards Roball manifested itself in very different ways: one child looked at Roball but made no attempt to catch it or to touch it; another was touching Roball while looking elsewhere. An overall similar situation was observed in Dautenhahn and Werry (Dautenhahn & Werry 2004). This made it difficult to evaluate our research hypotheses using the selected analysis technique. Other difficulties observed were that, by being a ball, Roball got thrown and tossed about, making it hard to distinguish self-propelled motion of the robot in such limited time. Regrettably there were also many distractions in the room used for the trials (the only one that was available): for example, other children from their group were playing nearby and could be heard but not seen. In addition, the educators at times helped or intervened, and even though they had been instructed to follow the experimental protocol each educator behaved differently with children throughout the trials, thus influencing the interactions.

Conducting a qualitative evaluation of the interactions that took place between Roball and each child provided richer observations from the trials. First, it was observed that Roball's face and sound generating capability made it an interesting toy for children. The fact that Roball spoke made some children feel uncomfortable at first, but this became a source of interest once they were familiar with the device. The presence of an educator during the trials was important in that regard, because it helped regulate the children's behavior. The educator was also able to put emphasis on what the robot was saying (by repeating what Roball said) and doing (using words to characterize the particular situation like "The ball is leaving" for instance). The buttons and the lights also attracted the children's attention. Second, Roballs dynamics, either when being pushed or moving on its own, generated interest. Roball did not move like a regular ball because its center of gravity is off-centered and changing. Children's interest in Roball's dynamics was manifested in different ways: looking at the robot without moving, going to catch the robot, holding it so that it did not move away. This partially explains why it was difficult to develop conclusive observations from the quantitative results. It also justifies the importance of qualitative evaluations, without which the observed interest from the children could not have been reported. For instance, this is how we identified that children played with Roball by trying to hold its face still while it tried to move. This game emerged from holding Roball's shell, making only the robot's face move and yielding the appearance of trying to get away from this difficult position.

Despite these experimental challenges, a general observation from these trials is that children enjoyed interacting with Roball-2. From the robotic perspective, the goal of designing an interesting autonomous mobile robot that has the potential to be used in child development studies was achieved. The trials conducted only address a small part of how Roball-2 could be used to study the child development of motor, intellectual, social, affective and language skills, but they do demonstrate its potential. In future work, in order to resolve the experimental issues identified, we plan to conduct trials with children in their natural living environments, similar to the experiments conducted with Roball-1 but following an evaluation method elaborated with human study experts. The revised evaluation techniques will involve longitudinal trials over 8 to 12 weeks periods which will be videotaped and systematically evaluated. Longitude studies potentially can reduce the influences caused by factors such as unfamiliar play spaces and unfamiliar people. Questionnaires filled in by parents and care-workers or teachers of the child will be designed to provide us with relevant information about the child, how he or she interacts with the robot and how such interactions affect his or her development. For these trials, additional prototypes of Roball-2 (four in total) would need to be designed to be robust enough to sustain such long-term experiments.

2.3 Roball-3: Adaptation through Children's Play Patterns

Robots that can adapt to children's play will have numerous benefits within a pediatric rehabilitation field. Adaptation would allow robotic systems to tailor their behavior to the individual, rather than the individual adapting their behavior to the robotic device. Through the detection of the personality type, it would be possible for the robot to adapt its behavior, for instance exhibit a slow unthreatening behavior when the robot detects a shy, cautious child. Similarly, the robot could exhibit a faster and more interesting behavior if it detects an active child. This would also have longitudinal benefits as the robot could change and adapt with the child overtime. If a child is at first cautious of the robot but overtime grows increasingly confident with it, the robot could adapt its behavior to compensate and tailor for this.

Salter et al. (Salter, Dautenhahn, & te Boekhorst 2004a; 2004b) developed a technique of using sensors onboard a robot to record and analyze interactions coming from children playing with the robot. They showed that personality type can be reflected in the way different children play with the same robot. It was discovered that the different types of children (e.g., boisterous, shy and cautious) produced play patterns that can be recorded and deciphered through sensors onboard the robot. Analysis showed that a 'fingerprint' of the child was left behind from the interactions the child had with the robot. However, their work did not go as far as adapting the robot to these findings.

Our goal is to further expand on this work and adapt a robot to the type of interaction it is receiving from a child. To achieve this, we have developed a new version of Roball, namely Roball-3. The objective pursued was to distinguish, from onboard sensor readings, what type of interaction the robot is receiving (e.g., being carried, being pushed, receiving no interaction, high levels of interaction), and adapt to this. Already completed are laboratory experiments and child-robot trials that indicate that it is possible to distinguish different types of interaction (Salter *et al.* 2005). In the laboratory, seven different scenarios of interactions that the robot might receive were devised. They consisted of such things as being carried, being spun, and receiving general interaction (e.g. being pushed and kicked). The robot is equipped with three accelerometers, one for each axis (X, Y and Z), and three tilt sensors, one for left tilt, one for right and one for forward/backward tilt. The accelerometers give more precise sensor readings which enable it to distinguish a greater variety of interactions.

The entire set of sensors did produce different readings during the scenarios that could later be distinguished through analysis. The child-robot trials also showed similar sensor results to those in the laboratory. We are currently developing an algorithm that will allow these interactions to be categorized in real time onboard the robot. Planned is a small set of trials in controlled conditions in which we hope to demonstrate Roball's autonomous adaptation to a child's interaction. Adaptation will be kept simple as it will be a proof-of-concept trial. It is likely to include the following: (1) Robot speeding up to high interaction levels and slowing down for low interaction, (2) Vocal messages responding to being picked up, spun and receiving no interaction.

3. MOBILE ROBOTS FOR CHILDREN WITH PERVASIVE DEVELOPMENTAL DISORDERS (PDD)

Children with PDD (e.g., autism) vary widely in abilities, intelligence, and behaviors: verbal communication can range from non-existent to limited phrases, to almost typical verbal skills. Children with PDD are characterized by a triad of impairments: social interaction, social communication and imagination. Additional to this triad, other behaviors may include resistance to change or unfamiliar surroundings, the inappropriate or repetitive use of objects and repetitive body movements or behavior patterns.

Using interactive robotic toys as part of the educational program is an interesting idea that has the potential of providing an additional tool in the rehabilitation process of autistic children. In 1976, the use of a remote controlled robot with a seven year old boy diagnosed with autism was, we believe, the first use of mobile robotic devices as a remedial tool for children (Weir & Emanuel 1976). In this work, the mobile robot was used to catalyze communication in the boy, and positive results were reported. The AuRoRA project (Autonomous Robotic platform as a Remedial tool for children with Autism) (Dautenhahn 2000; Dautenhahn & Werry 2002; Dautenhahn *et al.* 2002) is certainly now one of the best know initiatives within this subject area. To briefly describe the general aspects of this project, AuRoRA investigates how a robot can become a 'toy' that could possibly serve an educational or therapeutic role for children with autism. They hope to encourage children with autism in coordinated and synchronized interactions with the environment so to help them develop and increase their communication and social interaction skills (Dautenhahn 2000). Previously, the project conducted experiments with a mobile robot, based on the observation that autistic children prefer predictable, stable environments, and that they have difficulty interpreting facial expressions and other social cues. The robot used in these experiments was a Labo-1 mobile platform, a robot with a rectangular body and four wheels, eight infrared proximity sensors, and a positional heat sensor. The AuRoRA project was attempting to use the robot to bridge the gap between the complex and unpredictable world of human social behavior and the safe predictable world of simple toys. Other experiments conducted by AuRoRA include a humanoid doll, Robota (Billard 2000), engaged in interactions with autistic children. Robota has been deployed in various experiments including the investigation of the possible therapeutic effects of a humanoid robotic doll to autism therapy. Their approach was based on "the assumption that bodily interaction in imitative interaction games is normally an important factor in a child's development of social skills and that teaching of such skills (in a playful and exploratory context but nevertheless from an educational point of view focusing explicitly on specific types of interactions) could help children with autism in coping with the normal dynamics of social interactions" (Dautenhahn & Billard 2002). Robota has been used to investigate the effect of a robot's design (appearance) in facilitating and encouraging interaction of children with autism (Robins *et al.* 2004a). In a longitudinal study, Robota was also used with the aim to encourage imitation and social interaction skills. Different behavioral criteria (including Eye Gaze, Touch, and Imitation) were evaluated based on the video data of the interactions (Robins *et al.* 2004b). Related to this is the work of Kozima and Yano (Kozima & Yano 2001), suggesting that an infanoid robot (a humanoid torso designed to have a youthful appearance) programmed to play 'contingency-games' could benefit both autistic and typical children in learning communication skills.

Our incentives in becoming involved within the field of interactive mobile robots for PDD children differ from the AuRoRA project. Our motivation is to determine how a robot's motion, communication capabilities, and appearance can engage a child in interaction and once engaged, the ability of the robot to hold the child's interest in a hope of facilitating learning to develop social and communication skills. Each child is a unique individual with his or her own way of interacting with toys: these interactions may vary with age, interests, personalities and physical abilities. Since we can design robots in very different ways tailored to specific needs, we believe that it is important to investigate how the children react to the different shapes, sizes and functionalities of a variety robots.

3.1 RoboToy Contest

This initiative began in 1999 with the goal of finding ways to improve Electrical and Computer Engineering (ECE) education early on in the curriculum (Lachiver *et al.* 2002). We wanted to put students close to the reality of the profession by making them work on projects involving design and analysis abilities, autonomous learning, teamwork, communication skills and social considerations. We decided to provide them with a mobile robotic platform named ROBUS (Michaud *et al.* 1999). ROBUS is given to first year university students; they must assemble ROBUS and extend its capabilities by adding sensors, actuators, structural elements and by programming it using the Handy Board (Martin 2001) and the Handy Voice (a message-generating device that can be interfaced with a microcontroller) (Michaud *et al.* 1999). Our objective is to provide the students with a context for their learning, one that contained open challenges and would push the creativity and the ingenuity of the students. Teams are also encouraged to get students from other specialities (e.g., arts, education) involved. Through these initiatives, the project enables students to learn about the realities of designing and developing artifacts when technical considerations are coupled with social considerations. This was the basis and inspiration behind the RoboToy Contest (Michaud & Clavet 2001).

From a research perspective, the RoboToy Contest provides a setting that allows the design of many different kinds of mobile robotic toys for children with PDD. More than 100 robots have been developed by engineering students over the years, using knowledge on PDD provided through seminars, literature reviews, interviews with specialized educators, and results from trials done each year with a small sample of the robots presented at the contest. The objective of this section is to outline both the successes and failures of different robots abilities to create possible incentives for a child with PDD to open up to his or her surroundings. Trials lasted from single sessions of a couple of minutes to consecutive use over a five weeks period, as presented in (Michaud & Theberge-Turmel 2002; Michaud, Duquette, & Nadeau 2003).

These trials have shown that such devices, with their motion capabilities, their appearances, their sounds and their decision-making capabilities, have the ability to not only engage, but also to hold the attention of autistic children. Observations have shown that the children appear to enjoy interacting with the robots. Having removable parts seems to interest the children, if however they are of a suitable size: all small components or material that can be easily removed should be avoided for safety reasons (as is true of any toy). Rewarding games can be created by a robot reacting in a defined way when a child responds correctly to requests made by the robot. Examples of responses include dancing or playing music, having a rotative element activated for a short amount of time, or any action that can be simple to understand by the child. It appears that such responses can become an incentive for the child to continue playing with the robot. However, negative responses should be avoided, even if the child is not reacting or responding correctly to the robot. It was also demonstrated that robots can be programmed to change their behavior over time, like for instance having games with increasing levels of complexity as the child succeeds, or changing the actions of the robot so that the child does not just repeat a pattern but actually does what the robot is requesting. Changing behavior makes it possible to create more sophisticated interplay situations. Robustness of the robots has proved to be of prime importance. In earlier years some of the more fragile designs got damaged.

3.1.1 Interdisciplinary Collaborations

From an engineering perspective, we were able to evaluate the impact of the design choices in making the robots accomplish their intended behavior. At the time however, no expertise was available to evaluate the impact of the robots on the development of the children. To successfully analyze and evaluate the trials that we were conducting, a better understanding of PDD was required from what a typical electrical or computer engineer possesses. In 2002, a new collaboration with psycho-educators shed new light regarding human considerations in the design and the evaluation of the robots. Using the observations made during our previous experiences with the robots, a list of robot design specifications were outlined to compensate for the various deficits (i.e., visual deficits, auditory deficits, touching deficits; spatial perception deficits, language deficits and deficits in symbolic games) children with PDD may have (Michaud, Duquette, & Nadeau 2003). For instance, it was identified that visual elements like images and photos are more appropriate that just using words. The vocabulary used by the robot must be very simple, messages should be short (three words or less) and repeated frequently. Words should refer to concrete things rather than abstract notions. Games with the robot should be simple and easy to understand. Children with autism may have limited skills in sharing and imitation. Therefore, the robot should be designed to help children develop such skills.

Also from this collaboration with psycho-educators emerged a set of three experimental scenarios. They were not developed with the same target population in mind, but rather to outline important aspects on which engineering students should focus their designs. They were also intended to improve the validation and evaluation techniques of the specific human-robot interaction aspects. In all three scenarios, the robot must exhibit two different modes: (1) *Learning mode*, the robot teaches the child about something, and (2) *Evaluation mode*, the robot is used to see if the child has learned the lesson. The scenarios were introduced in 2003 to engineering students as guidelines for the design of robots for the RoboToy Contest.

1. **Recognizing emotions.** The first scenario is aimed at investigating if a child can recognize emotions being portrayed by a robot. The robot should attempt to exhibit different emotions (e.g., joy, sadness, anger). The emotions should be expressed through the use of facial expressions, movements[2], sounds, lights or vocal messages. The goal is to see if the child can recognize the correct emotion.
2. **Identifying action.** Through the use of pictograms, vocal messages, motion or other representations, the second scenario is to develop a system that can help children to learn about an action (e.g., teeth brushing) that is associated with objects or entities in the world (a tooth brush). Whilst in the learning mode, the robot exhibits an action selected by the child pressing on a pictogram. During the evaluation mode, the robot exhibits an action, and then the child has to select the appropriate pictogram. The location of the pictograms can be interchanged on the robot to ensure that the child has successfully recognized the action, and not just the position of the pictograms on the robot.
3. **Developing language.** The third scenario is oriented toward developing language skills. In learning mode, the robot must present objects to the child and vocally name the object. Then whilst in evaluation mode, the robot names the objects without presenting them to the child, and notes if the child selects the appropriate object to the request.

The winners of the RoboToy Contests are determined by a jury with three PDD experts, three engineering experts, and two marketing experts. Since real trials cannot be conducted during the contest, the PDD experts evaluate the potential benefits these designs may have as potential pedagogical tools with PDD children. The 2003 and 2004 winning robots for each scenario are shown in Figure 4. These robots illustrate that there are many different, clever and yet simple ways of designing robots for these scenarios. The prototype can take the form of well-known characters or be completely novel in design. For the emotion scenario, the 2003 winning robot used a rotating cylinder to change the

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[2] It appears that motion and form can independently contribute to the recognition of emotion from human movement (Pollick *et al.* 2001).

Fig. 4. Winners of the 2003 and 2004 RoboToy Contests.

facial expression of the robot, while in 2004 the winner directly modify the position of its eyebrows and its mouth. For the action scenario, the 2003 winner was a pirate-robot demonstrating four actions suggesting how to play with a boat. The corresponding 2004 winner was quite different, teaching the child how to sing, dance and to say hello by waving a hand. Finally, for the language scenario, a cow-robot equipped with removable plateaus of objects won in 2003: it aimed at teaching how to name different animals present on a farm. The corresponding 2004 winner was a mobile head with removable parts (eyes, nose, ears, mouth), the robot is intended to help children learn to name these body parts. Each of these robot's cost less than a 1000 $CAD in materials.

Overall, the addition of the experimental scenarios to the RoboToy Contest has provided the students with important knowledge to design robots better adapted to the problem domain, while still allowing diversity in the design. Engineering students were able to focus more on the design aspects of the robot, instead of discovering what can benefit or be interesting to use with children with PDD. By having PDD experts on the RoboToy Contest panel and by conducting trials with the prototypes over the years, engineers and psycho-educators incrementally learned what was useful and what can be achieved with robotic technology. A lot is still unknown about PDD, and mobile robots are new devices with capabilities still to be discovered. Combining the two disciplines means even greater learning by both roboticists and psycho-educators. We believe that our experience with the RoboToy Contest provides evidence that the multi-discipline knowledge shared throughout an iterative process can result in improved design that ultimately benefits the intended user, in this case children with PDD.

3.2 Tito the Robot

Another part of the project to develop robot for children with PDD was initiated in 2003. It involved a longitudinal study between a robot called Tito, shown in Figure 5, and children diagnosed with autism. The study was conducted over several weeks by psycho-educators. The objective was to investigate if a mobile robot can make a child imitate. The hypothesis is that if a child can imitate a robot, the child will become interested not only in objects in general, but in an object that somehow emulates similarities to human beings through the object's mobility and anthropomorphism.

First, we developed four experimental scenarios that illustrate how the robot could be used in such study:

- Familiarization. To begin, the robot starts by telling the child its status while moving in the room: "Me robot", "Me happy" (and smile), "Me walking" (and move). The robot would also point and identify different objects in the room.
- Identification of people. A photo of people known to the child are placed on a wall, and the robot moves in front of a photo to either identify the person on the photo or ask the child questions like: "Where's Mom?", "Where's Dad?".
- Identification of body parts. The robot points to one of its body parts and says which part it is; then the robot asks the child to point to his or her corresponding body part.
- Imitation of actions. The robot asks the child to imitate the same actions it is performing, for example, moving forward, backward, and turning.

Fig. 5. Tito the robot: concept (left) and prototype (right).

In all of the scenarios, if the child correctly responds to the robots requests, the robot smiles and raises both its arms; if the child incorrectly responds to a request, the robot just says "no" and shakes its head. At the end of each scenario the robot leaves the room by saying: "Robot done", "Door", "Bye bye".

Designing a mobile robot that can implement such scenarios is a challenge, even if teleoperation is used to conduct the navigation and respond to the child's interaction. There were four major design considerations: (1) *Overall Requirements* - The robot should be able to fulfill the list of abilities necessary for the four experimental scenarios; (2) *Longevity Study* - The robot should be able to correctly function for a period of approximately two months; (3) *Operator* - The robot is to be operated by non-robotic experts; (4) *Experimental analysis* - Knowledge about how data will be analyzed during evaluation can influence the design, sensors and capabilities of the robot.

The robot developed to address these specifications is named Tito and is shown in Figure 5. Tito is approximately 60 cm tall and is colored, red, yellow, and blue. Its clothes are washable and made of soft material. It uses wheels to move, but its structure shows two feet and two legs. It has two arms that can move up and down rapidly, a head that can rotate (to indicate 'no') and rise up (to express surprise), a mouth (for smiling), two eyes, a nose and hair (made from fiber optic cable to illuminate). Also, since we were interested in measuring eye gaze toward Tito, a small wireless microphone-camera device was installed in one eye of the robot. Different parts of Tito's body can be illuminated and it is able to sense if it is being shaken or if it has flipped over. The robot is also equipped with ultrasonic range sensors for simple obstacle avoidance. Tito generates vocal requests through pre-recorded messages. A wireless remote control (using a video game controller) was designed for teleoperation, and an on-board microcontroller enables pre-programed sequences of behaviors (motion and vocal messages). Examples of pre-programed behaviors are: moving the left arm while saying goodbye, expressing happiness by moving its arms, singing and rotating on the spot, or shaking its head to indicate no. Tito records and stores internally the timing between the interactions of the child (from sensory data and according to the experimental scenarios). Tito also emits a sound when it starts the execution of an experimental scenario, allowing synchronization of video data recorded with an external camera. The activation button of Tito is hidden at the bottom of the robot so that the child is not tempted to play with it. Tito was built in less than 6 months using modular distributed subsystems we had previously designed or used on other robots (e.g., energy monitoring, locomotion control, remote operation, sensing) (Michaud *et al.* 2005b), and a similar sound generating device used on the RoboToys and Roball. Tito cost around 2500 $CAD in materials.

Trials were conducted with Tito and four autistic children (3 boys, 1 girl, homogeneous profiles) between 4 and 5 years of age (average 5 years and 1 month old). A child was selected if they were diagnosed with autism as specified by the ADOS-G (Autism Diagnostic Observation Schedule-Generic) module 1, and showed severe disorder in receptive and expressive language skills and deficits in symbolic games. All children were part of the same intervention group in their school. The trials were conducted in a 15 m^2 room, equipped with a chair and a toy familiar to the child in the center of the room, the imitating agent (Tito for two children, the experimenter for the other two children), a video camera and a helper. When Tito was used as the imitating agent, the experimenter was in a corner of the room, teleoperating the robot according to the experimental scenarios. Each child played individually with the robot in 10 minutes sessions, conducted three times per week over an eight week period. Thus, each child spent a total of 4 hours with the robot. All of the trials were recorded.

Overall, preliminary results (Duquette 2005) show that imitation of body movements and familiar actions occur more frequently with the experimenter than with the robot. However, attention sharing and imitation of facial expressions occur more frequently with the robot. Another interesting observation is that children figured out that Tito was teleoperated, which generated enthusiastic interactions between the child and the experimenter. This concurs with Robins et al.'s (Robins *et al.* 2004a) observation that a robotic device can be used as a mediator for autistic children. In future work, our intent is to use Tito to identify useful adaptive capabilities that would allow Tito to autonomously interact with children with PDD.

4. Perspectives

Originating from robotic incentives, these two projects demonstrate that mobile robots with many different capabilities can be designed to be robust, safe, simple to use and beneficial in child development applications. Modifications can be made to general purpose, commercially available, mobile robotic platforms to make them suitable for use in child development applications. However, since mobile robotic technology is still in an early stage of development, such platforms require very specialized knowledge and periodic maintenance. As previously argued about traditional manipulator arms, we believe that the use of mobile robotics in rehabilitation is likely to grow in novel applications areas where the robots are not so obviously robotic devices (Hillman 2003): this requires specifically designing robots for children-robot interaction. As creators of these intelligent robots, we have complete control over their characteristics: we can decide how robots react to different types of interaction, activate or deactivate modes of interactions, control adaptation in the robot's behavior, remove or add components (hardware or software), change the overall design and appearance (to attract attention, to make discoveries or to exploit a priori assumptions about its capabilities (Goetz, Kiesler, & Powers 2003)).

Designing mobile robots to interact with children in unconstrained and unstructured conditions undoubtedly provides unique challenges and inspiration. Two general observations can be made from our experience:

1) Mobile robots designed for child-robot interaction benefit from rapid real world exposure and prototyping, and from human science expertise. By experimenting in real world environments with children and safe mobile robots (such as those presented in this paper), simply through observation we were able to assess the usability and suitability of the designs, the children's perception, their like and dislikes. Such exposure has brought about valuable insights even when the robots were just proof-of-concept prototypes or when experimental protocols had yet to be elaborated. This immediate exposure leaves room for refinements in the design before conducting extensive studies. Exposing robots to the real world is a discovery process, and seeing them perform help generates ideas for new technologies, novel applications and studies. It also helps to identify both successes and failures in human-robot interaction. We believe that it is important to report both of these in order to "contribute to the volume of knowledge" (Hillman 2003).

2) Mobile robots interacting with children bring new opportunities and challenges in experimentation, evaluation and analysis. From our experience, conducting trials with infants or children and robots is highly challenging. This is further complicated when the children have special needs such as PDD. In that regard, Robins et al. (Robins *et al.* 2004a) indicate that "the effort to realize user studies with robots is immense and poses significant obstacles to the advancement of research in the field". Areas that must be tackled include identifying the role and the benefit of the robot to users, assessing the test population and their psychological profiles, arranging the experimental setup, determining the duration of the trials and setting up an experimental methodology to gather solid scientific data. These are all extremely engaging tasks that cannot be improvised. Just determining whether to use quantitative or qualitative methodologies is a research issue on its own, with arguments for and against each area of expertise. This makes it hard for roboticists to make an educated deduction in order to select the best one for a particular design. Quantitative evaluation usually requires second by second analysis of videotaped data and cross-validation of measurements when more than one evaluator is involved. On the other hand, interactions are dynamic processes that are difficult to evaluate just by looking at the end results or the individual steps taken when they occur. Qualitative approaches based for instance on descriptions or periodic reports of interactions over short or long periods of time might bring added benefit in that regard.

Taking into account these observations, progression must include collaborations from varying areas of expertise. The amount of knowledge, expertise and skills required in robotics and human sciences are so vast that they cannot be addressed individually. People outside of robotics rarely have a realistic idea of what robots can truly achieve, and whilst roboticists can greatly contribute in designing robotic prototypes, they rarely have the knowledge or expertise to identify the needs of human users, e.g., children with special needs. Things that may seem trivial to pediatric specialists are not for roboticists, and the inverse is also true. Both can benefit greatly from cross-fertilization of the fields through experts contributing knowledge from their own area of expertise, thus, creating at the same time new opportunities in robotics, child development studies and pediatric rehabilitation therapy.

The RoboToy Contest illustrates the value of such collaborations, even without involving large teams of highly paid experts and expensive equipment. Every year the overall expertise and guidance improve in all areas: students learn from past designs, and psycho-educators and therapists observe what can practically be achieved with robots. This helps them to be more realistic in their advice and requests regarding the robot. This leads to the creation of robots better suited for the end user and the intended application domain.

Recommendations for Future Research

The research initiatives described in this paper are still on-going, and we will advance by seeking and fostering active collaboration between roboticists and pediatric specialists. From a robotics perspective, we will continue to improve our designs both in the laboratory and by making them available for experiments. Truly superior robots must be able to function effectively in their intended domain and must do so with minimum maintenance. Untrained or naive users (e.g., infants, children and non-robotic experts) must be able to operate these robots for long periods of time. To achieve this goal, robots require adequate mechatronics, decision-making algorithms, devices and tools. We also intend to improve our robot's capabilities to achieve more natural interactions with people. Natural interaction is especially important with untrained or naive users, and even more so if special needs are taken into account. We believe that mobility is one important element of natural interaction, as demonstrated in this paper. We are also currently improving the robot's capabilities by making it omnidirectional, which will allow increased and more natural locomotion capabilities (Michaud *et al.* 2005b). Another improvement being added is the ability to localize, separate and identify sound sources. Knowing where the sound source (a child, for instance) is located could contribute to creating an increased sophistication and natural way of interaction with a robot, making it for instance move toward the child and react to vocal responses. The field of artificial robotic audition is still in its infancy, and only a few have addressed this topic (Nakadai, Okuno, & Kitano 2003; 2002). We have however developed an approach using an array of eight non-expensive microphones to localize and extract sound sources in real time (Valin *et al.* 2003; Valin, Rouat, & Michaud 2004). In future work, we want to see how this approach could benefit robots interacting with children acting in a pediatric rehabilitation role.

From a pediatric perspective, we have barely started to demonstrate the potential benefits of using such devices with children. Studies like the one presented by Besio (Besio 2002), regarding the selection and the use of assistive technology to allow children with motor disabilities to play with toys, is a good example of the various dimensions to be considered when studying interaction with children. Such studies are rich sources of ideas for roboticists to design mobile robots for such application, robots that can be used in the evaluation methodologies established by pediatric rehabilitation experts. Our studies and research projects conducted so far clearly demonstrate and highlight the abilities of robotic technology. The motion the robot produces is a source of novelty in interplay situations, allowing implicit (from the perception of intentionality in moving elements innate to humans (Premack 1990; Dautenhahn & Werry 2004)) or explicit (by changing its behavior, by inviting the child to move or by going toward the child) adaptation to children and the environment, and the ability to keep children engaged. We plan on continuing to explore these avenues by fostering collaborations with pediatric specialists.

Robots show great potential to become remarkable technological tools for educators, psychologists (Caci, d'Amico, & Cardaci 2004) and rehabilitation clinicians. Through playing with these devices, children can develop new skills and capabilities, and while at the same time, as Prazak et al. (Prazak *et al.* 2003) wrote, "simply make them happy."

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