Roball, the Rolling Robot

François Michaud and Serge Caron

LABORIUS - Research Laboratory on Mobile Robotics and Intelligent Systems

Department of Electrical and Computer Engineering

Université de Sherbrooke, Sherbrooke (Québec Canada) J1K 2R1

http://www.gel.usherb.ca/laborius

Abstract

Designing a mobile robotic toy is challenging work. The robot must be appealing to children and create interesting interactions while facing the wide variety of situations that can be experienced while playing with a child, and all at a reasonable cost. In this paper we present Roball, a ball-shaped robot that moves by making its external spherical shell rotate. Such design for a mobile robotic toy shows robustness in handling unstructured environments and unconstrained interactions with children. Results show that purposeful movements of the robot, its physical structure and locomotion dynamics generate interesting new games influenced by the environment and the child.

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Introduction

The 1980s were the years of the personal computer revolution, followed in the 1990s by the WWW/Internet revolution with the growing interest in the concept of interaction, creating interesting and appealing ways of exchanging information between computers and users. The primary focus for the next decade is interaction (not just for Internet but with electronic devices that operate in the physical world), using sensors as the key technology to create what can be called "smartifacts". (Saffo 1997)

Interaction is surely one concept of great importance for the toy industry, and commercial interest for interactive toys is expanding rapidly. Robotic pets like *Furby*, *Poo-chi* or the sophisticated robot-dog *Aibo* from Sony and part of the MUTANT project (Fujita, Kitano, & Kageyama 1998) are now entertaining children of all ages. Robotic dolls like *My Real Baby* from the association between Hasbro and iRobot inc., or *Miracle Moves* from Mattel, are making their way into our homes. While it has been thought that mobile robots would initially be commercialized to accomplish house chores like vacuuming and lawn mowing, technological development and research are still required to reach the level of precision and effectiveness to make such task-oriented robots be widely used, working as good or better than humans. Developing a robot that has to interact in interesting ways with one or many users is a much more reasonable goal to achieve. A child will tolerate that his or her robotic toy sometimes stumbles or falls for some reasons, or that it does not react appropriately to some events: this will just be part of the game, and the robot's performance will be evaluated based on its ability to entertain.

However, this does not mean that designing robotic toys is not without its challenges. Children are extremely hard on their toys: they grab them, throw them, kick them, put them in places they should not be in (dirt, water, modeling compound, ...), etc. Electronic products are easily affected by these conditions. High tech toys would usually cost more because of the additional processing, electrical and mechanical components required to create interactions with the child, and parents will think twice before paying more for something that might get damaged easily. The ability to create appealing and meaningful interaction is also fundamental. The physical appearance of toys is still essential, but now interaction is an additional concern and can be done in various and novel ways:

speech, sounds, facial expressions, visual cues and movement. These characteristics all contribute to the life-like quality of robotic toys. In that regard, the ability to navigate autonomously and purposefully is especially interesting since the variety of situations that a mobile robot would encounter in a household or playroom environment (which will surely not be a uniform surface free of obstacles) also presents important challenges for robots.

So the goal is to design a mobile robotic toy that can manage unconstrained interplay situations experienced while interacting with children in real life settings, and all at a reasonable cost. Children like to play with a lot of things, and many different types of robotic toys can be imagined. To design such robot, we followed a spiral model for engineering design (Pressman 1992). The idea is to outline initial requirements, formulate solutions, implement a prototype and evaluate it, and repeat this cycle with increasing levels of complexity and completeness. This paper reports on the first cycle of this design process of a mobile robotic toy. Mainly, it explores the use of a rolling robot named Roball as a mobile robotic toy. Roball is a ball-shaped robot that makes its external spherical shell rotate for locomotion. We present the proof-of-concept prototype and observations made of children interacting with the robot in unconstrained conditions, in order to evaluate the potential of having such robot be used as a toy and how its design can be refined and used for entertainment or educational purposes, and to study human-robot interactions.

The paper is organized as follows. Section 2 first outlines design specifications that we consider important for designing our mobile robotic toy. Section 3 describes the hardware and locomotion mechanism of Roball. Comparison with other rolling robots is also provided. Section 4 then addresses how we use Roball as a mobile robotic toy, with a description of the software design. Observations made of children who played with Roball are presented. Section 5 presents an analysis of the observations made and outlines potential directions to take in designing mobile robotic toys.

2. Design Considerations

Four elements guided our design of Roball in this first cycle of the design process:

- **Operation in Unconstrained Environments**. Children like to play with toys in all kinds of places, indoor and outdoor. In such context, a mobile robotic toy must be capable of working on different operating surfaces (wooden floor, ceramic, carpets, etc.), and it might encounter a great variety of objects (other toys, shoes, clothes, etc.), obstacles (walls, couch, table, chairs, stairs, etc.) and entities (dog, cat, people, etc.). The locomotion mechanism and the physical structure of the robot have a direct influence on this ability: a wheeled robot may flip over or on the side, or it may get lifted on top of an object; a walking robot may trip on something and accidentally fall on somebody; a heavy robot may cause a lot of damage falling down the stairs; a powerful robot may be capable of moving furniture around if some of its parts get stuck to some objects like chairs, and may again cause potential accidents. Careful considerations must be taken in designing robots that are well adapted for the diverse operation conditions that arise in household environments.

- **Physical Robustness**. As indicated in the introduction, children can be extremely hard on their toys. High tech products are very sensible to shocks and rough usage, which are common with toys. Since a mobile robotic toy, by using sensors, actuators and a processing component to interact with the environment and children, will surely cost more than non-electronic toys, special care must be taken to protect the parents' "investment" in the toy. Indicating the age range is one way of preventing misuse of a toy by younger children, assuming that older children will carefully use the toy. However, it is not a foolproof solution because once the toy is out of the store, there are no guarantees that it will be properly used or that a child will respect the age restriction. And for high tech toys that can move around autonomously, or doll-like toys that represent pets or characters (like a Furby), it may be difficult to enforce age restrictions. For example, we have personally witnessed a one year old boy getting his hands on a Furby doll (recommended for children 6 years and older) that got rapidly damaged. The damage would have been even worst (and costlier) on *Aibo*.
- **Interplay and Interaction**. Our principal consideration is to design a robot that can navigate autonomously and purposefully in the environment. This is a new capability for toys, since actual mobile toys are either teleoperated or moving in the same direction as set by the child. The objective is to see how autonomous navigation by a toy may create interesting new interactions with children. Also, the toy must not be too big or too heavy to be manipulated by children. Finally, the mobile robot must

be easy to use and generate interactions that are simple to understand.

- **Minimal Cost and Complexity**. The complexity and obviously the cost of robotic toys are directly affected by the ways the toy can interact with the child. For example, the $35 US Furby doll can talk and respond to sounds and touch, using one motor and a gearing mechanism to control the different moving parts. However, *Aibo* is equipped with lots of motors, a camera, a powerful microprocessor and various sensors, making the robot able to move autonomously in the environment. This robot is also in the thousand dollars price range. Adding locomotion and autonomous navigation capabilities to a toy will surely cost more because of the need for more motors and processing components, and the challenge is to come up with a design that maximize what the robot can do at a minimal cost. To be a good product for the consumer market[1], a toy should cost around $40 US, which implies that the production and packaging cost must be less than $10 US.

Addressing all of these considerations is surely a challenging endeavor, and many different design configurations can be proposed and studied. In our case, we addressed the problem by trying to optimize the robot's physical structure, its hardware and its software, to come up with an appropriate design using current technological components (in opposition to developing a concept with technologies that are yet to come).

The solution that we came up with involves encapsulating a robot inside a sphere, and to use the sphere to make the robot move around in the environment. Designing a spherical robot offers the following advantages:

- The spherical shape allows the robot to face all kind of obstacles, surfaces and interplay situations. A rolling ball usually follows the path of least resistance. It has less chances of getting stuck on top of an object or in between the legs of a chair. In contrast, a wheeled robot may see its caster wheel works very poorly on a carpet, or the robot may overturn when trying to move over a boot for example.
- The shell protects the robot's circuitry against shocks, dirt and other things that high tech products are sensitive to. No assumptions on the child age or on the way the toy must be handled are then necessary.

[1]According to Doug Glen, Chief Strategy Officer at Mattel, during an invited presentation at the *Workshop for Interactive Robotics and Entertainment*, Pittsburg, May 2000.

- Children are used to play with ball-shaped objects, making the robot implicitly appealing. Kicking is to be expected, more so than with another kind of toy robot, making robustness even more important. But contrary to an usual ball, a robot ball may respond in different ways (like trying to escape, stop moving, asking the child to stop, etc.) when a child is too hard with it.
- By putting everything inside a sphere, the robot's physical structure is not complicated. Also the robot can move with a minimal number of parts and components (as little as only one motor for propulsion), which minimizes the cost of the robot. No complex mechanism is required, and large scale production and assembly should not be very complicated.

Supported by these arguments, what need to be validated first are the feasibility of the locomotion and control mechanisms with a proof-of-concept prototype, and implement a simple behavioral scenario to do exploratory experiments with children in order to identify if interesting interactions and interplay situations would arise with such robot.

3. Roball – the Robot

Our first prototype built in 1998 is shown in Figure 1. It is 6 inches in diameter and weights about 4 pounds. This prototype is made of a plastic sphere (bought in a pet store) made of two halves that are attached to each other, a Motorola 68HC11 microcontroller board[2] and other components commonly distributed by electronic suppliers. This is sufficient for the proof-of-concept prototype, considering that a more detailed design could be done if this initial prototype reveals the concept to be appropriate. The overall cost is less than 100 $US.

Figures 2 and 3 illustrates the propulsion mechanism of the robot. The robot is made of a plateau on which all components are attached. Two DC motors are located on the side of the plateau, perpendicular (on the horizontal plane) to the front heading of the robot. These motors are attached to the extremities of the spherical shell. These motors make the center of gravity of the internal plateau move forward or backward, making the robot move. The speed of the motors is regulated according to longitudinal inclination of the internal plateau, keeping the center of gravity of the robot close to the ground. Steering

[2] Note that other microcontrollers could have been used.

Fig. 1. First prototype of Roball.

is done using a counterweight (a 12V 1.2Ah nonspillable rechargeable SLA battery in our prototype) mounted on a servo-motor. This allows the robot to tilt on one side or the other as the shell rolls.

3.1 Comparison with Other Spherical Robots

Bhattacharya and Agrawal (Bhattacharya & Agrawal 2000) classify spherical robots in four categories:

- Single wheel resting on the bottom of the sphere (Halme, Schonberg, & Wang 1996). The concept was validated by having the robot teleoperated by a radio joystick.
- A hollow sphere with a small car resting on the bottom (Bicchi *et al.* 1997). The concept is similar to having a gerbil run inside a sphere. The robot received commands from a remote computer using a radio link.
- A sphere containing a universal steering wheel resting on the bottom (Ferriere & Raucent 1998). This concept is related to the previous one, without the non-holonomic movement of the propeller inside the sphere.
- A sphere with two side rotors, mutually perpendicular, plus one rotor attached to the

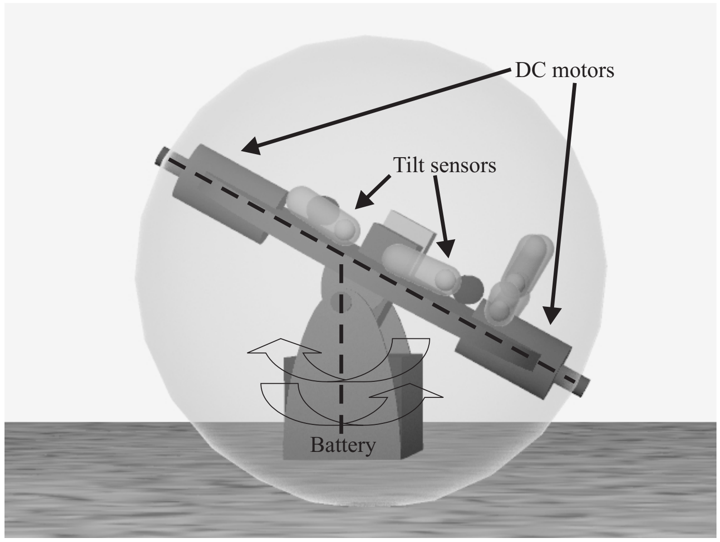

Fig. 2. Rear view of Roball's propulsion and steering mechanisms, as Roball turns to the right.

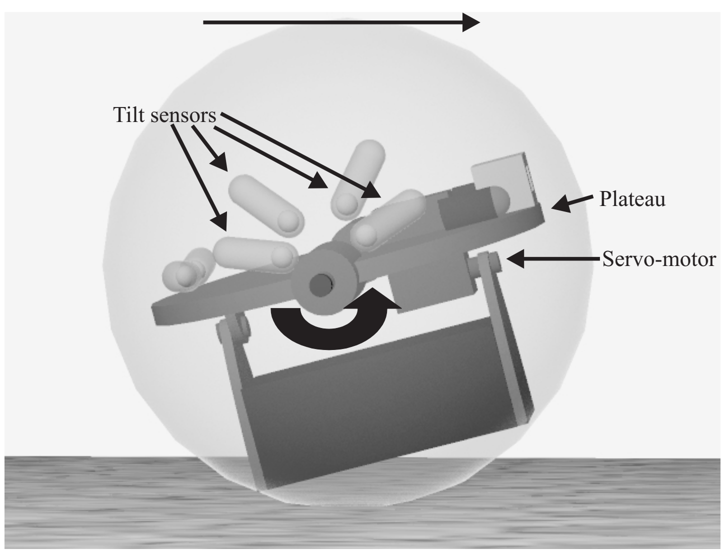

Fig. 3. Right side view of Roball's propulsion and steering mechanisms.

bottom of the sphere (Bhattacharya & Agrawal 2000). It is the angular velocities of these internal rotors turning on themselves that make the robot move. Control of the robot was done remotely based on information derived from a camera located on top of the experimental field.

Our concept would fit in a fifth category of spherical robots that uses motors attached to the sphere to make it rotate. After having built our first prototype of Roball, we discovered other similar designs:

- The Solar Ball Kit commercialized by Images Company Inc. (not sold anymore) is a spherical robot that uses solar energy in its first version. In the second version, when light is detected a battery is activated and the robot moves. No steering mechanism is provided. Released in 1998, the BEAM MiniBall is also a rotating robot that has a similar behavior. It is based on a design by Richard Weait of Toronto who built, in the 1993 BEAM Robot Olympics, a self-contained solar-powered robot in a pet store hamster ball like the one used for the first prototype of Roball.
- The Orbot rollerbot is a rolling sphere robot teleoperated using a TV remote control.
- Toy Biz Inc. (Arad, Pitrone, & Jeffray 1996) has a patent on a self-propelled toy ball which plays musical tunes and generates sound effects. Once energized, the electronics of the ball operate to propel the ball and simultaneously activate an integrated circuit sound effects chip which plays a musical tune. When the ball bumps into something, the propulsion mechanism is disengaged and the circuit then plays a randomly selected pre-programmed sound effect. Thereafter, the propelling mechanism is again activated and the ball resumes playing the musical tune.
- Cyclops is a teleoperated robot (Chemel, Mutschler, & Schempf 1999) designed in 1998 by the Field Robotics Center of Carnegie Mellon University. Instead of using a counterweight for steering, Cyclops use a rotational mass to make the robot pivot in place. While this actuator makes Cyclops holonomic, the authors report some difficulty in making the robot rotate with precision.

Roball significantly differs from these products by using onboard microcontroller and sensors to make the robot navigate autonomously in the environment. Compared to Cyclops, Roball is non-holonomic and uses much simpler components and offers a less expensive design. Finally, it is worth noting that Roball's locomotion mechanism differs from other round-shaped robots like the Gyrover (Xu *et al.* 1998), which is a one-wheel robot. Roball can rotate on all of its external surface.

4. Roball – the Mobile Robotic Toy

Using Roball as a mobile robotic toy, the objective is to observe how a ball-shaped robot can generate interesting and novel interplay situations with children by moving autonomously in the real world. Contrarily to current robotic toys, our objective is not to create the illusion that Roball is an entity that needs caring and nurturing. Other toys like *Furby* and *My Real Baby* are more appropriate for that because their appearance are directly linked to such type of interactions. Similarly, we found important to generate interactions with Roball that are in direct relation with its dynamics and its structure.

Roball is programmed to follow a deterministic play routine, and act according to the unexpected situations experienced in the environment or caused while interacting with a child. The behavioral scenario implemented with Roball involves autonomous navigation in the real world, and also communicating requests and needs to the child. These are communicated by vocal messages using an ISD ChipCorder, a single chip device for voice recording and playback. Specific messages are memorized in EEPROM and are invoked by the microcontroller of Roball.

To provide inclination measures using simple sensors, we installed tilt sensors on the robot: four tilt sensors for longitudinal inclination, and two for lateral inclination. Longitudinal tilt sensors are located on the right side of the robot (shown in Figure 3) and the lateral tilt sensors are on the back (shown in Figure 2).

The following subsections describe the software design of Roball used as a mobile robotic toy, and the experimental observations made of children playing with Roball.

4.1 Software Design

The approach used to control the robot must include efficient software mechanisms for sensing the environment, for low-level control of the robot's actuators, and also for managing the goals of the robot and create interesting interactions with the child. Following the guidelines of a computational architecture (Michaud, Lachiver, & Dinh 2001;

Michaud & Vu 1999; Michaud 1999), the basic idea is to have behavior-producing modules (also called behaviors) control the actuators according to sensory data and the state of the robot, and dynamically change the selection of the behaviors over time. The selection of behaviors is done according to environmental states, the goals of the robot and reasoning done about the world.

Behaviors are implemented as individual processes that get activated or terminated according to the goals of the robot. These goals are managed based on internal variables called motives. A motive is a variable that has an energy level and an activation level, both ranging from 0 to 100% (Michaud & Vu 1999). The energy level can be influenced by various factors: sensory conditions, the use of behaviors associated with the motive, activation of other motives, and cycle time (for cyclic occurrences). The energy level is computed by the equation $E_m = \sum_{j=1}^{n} w_j \cdot f_j$, where f represents n influencing factors, weighted by w, affecting the motive. The activation level of motives is used to determine the recommendation of behaviors by the *Goal Manager* module, and is derived from the energy level. In this implementation, a motive is activated when its energy level reaches 100% and remains active until its energy level reaches 0%. The energy level reflects the history of past events that influenced a motive, while the activation level is used by the *Goal Manager* module to activate behavior-producing modules.

As shown in Figure 4, four behaviors are used to control the velocity and the direction of Roball, using Subsumption (Brooks 1986) as the arbitration mechanism. These behaviors are, in order of priority: *Emergency*, used when the robot comes in contact with an object; *Steer*, to position the counterweight in a desired steering position and change the robot's heading; *Straight* to make the lateral inclination of the internal plateau stay parallel to the ground, making the robot goes straight ahead; and *Cruise* to make the robot move forward. These behaviors allow the robot to wander in the environment and take action when it collides with an obstacle. When the robot comes into contact with an object, the shell stops rolling and the internal plateau makes a full rotation inside the sphere. This is detected using the longitudinal tilt sensors, allowing the *Emergency* behavior to stop the motors and stabilize the internal plateau. The full rotation of the internal plateau is usually enough to make the robot move away from an obstacle, but other actions could

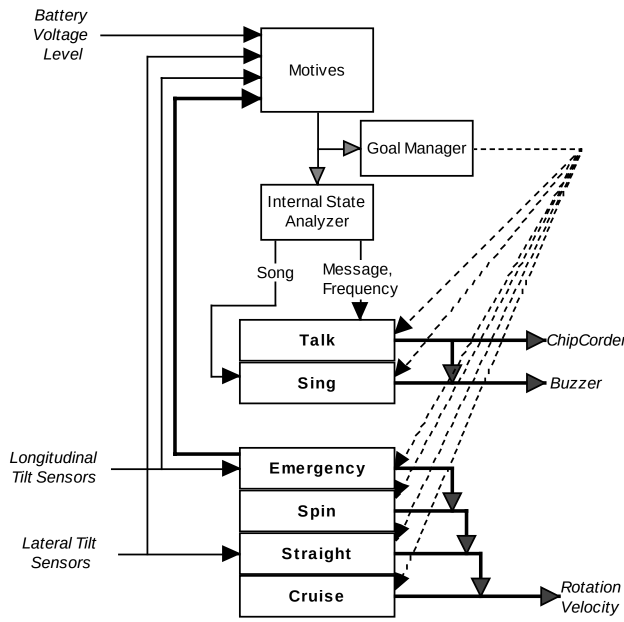

Fig. 4. Decision modules used to control Roball.

also be implemented (like backing away and steering in one direction, or using the *Steer* behavior as used with the *Distress* motive).

In addition to these locomotion behaviors, a behavior named *Talk* is responsible for generating the proper message at a specified frequency using the ChipCorder, and *Sing* plays songs using a simple buzzer. We find it more appropriate to use specific behaviors for communication instead of, for instance, generating messages directly by the navigation behaviors. This allows messages to be generated based on the goals (motives) of the robot and on an analysis of what is happening to the robot over time, instead of only reacting to events in the environment. This analysis is done by the *Internal State Analyzer* module.

The motives used in this implementation with Roball are shown in Figure 5. The general state of Roball is determined by the *Goal Manager* module using three general motives:

- *Hungry*. This motive verifies that the battery voltage level is greater than a preset threshold. If not, the *Cruise* behavior is deactivated to make the robot stop, and Roball asks to be recharged.
- *Distress*. This motive examines the frequent use of the *Emergency* behavior (using

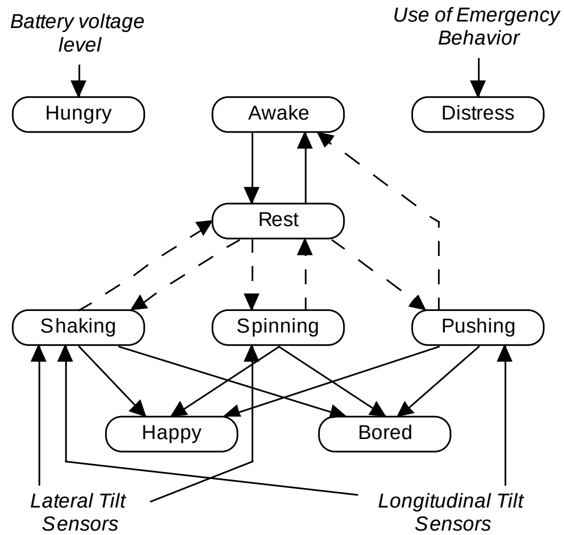

Fig. 5. Motives used by Roball.

the link represented in bold in Figure 4), which is a sign that Roball is having trouble moving freely. Every time the *Emergency* behavior is used, Roball apologizes for having hit something. If *Emergency* is used frequently in a short period of time, Roball asks for help and the behavior *Steer* is activated to try to move the robot out of trouble.

- *Awake*. This motive is used to simulate sleeping periods during which Roball is not playing with the child. When *Awake* is not activated, all behaviors are deactivated. Otherwise, Roball is allowed to move and to interact with the child. Coming back from sleep, the robot says hello and plays a short song. Roball stays awake longer when no distress situations are experienced or when the robot is not moving a lot.

When awake, other motives can be used. Roball is programmed to wander around in the environment until it decides to rest using the motive *Rest*. This motive deactivates the *Cruise* behavior, stopping the robot from moving for a certain period of time (determined randomly). As shown in Figure 5, during resting, the robot is allowed to interact with the child in one of three ways (also selected randomly): Roball can ask to be spun, to be shaken or to receive a small push to start moving again. Spinning is detected by a particular state of the tilt sensors that only occurs when the robot is being spun: both lateral tilt sensors are in an open state because of the centrifuge force. Shaking is recognized when the state of any of the tilt sensors changes frequently, while pushing the robot when at rest is detected by a frontal inclination of the internal plateau. Three motives, *Spinning*, *Shaking* and *Pushing* respectively, are used to monitor these requests and the response from the child. For example, if the child shakes Roball when it asks to be spun, then the robot asks the child to stop. When spinning is requested, Roball can indicate that it feels dizzy or that it wants to get another spin, depending on how long it span. When spinning, a message expressing excitement is also generated. If a response is given to a request for spinning, shaking or pushing in a reasonable amount of time, then Roball thanks the child. This action is monitored by a motive named *Happy*. If the child does not respond to the request, then a motive named *Bored* gets activated and the robot indicates that it is getting bored. When the energy level of *Rest* drops to zero, these interactions stop and Roball starts to move again. Also, for the pushing request, the *Rest* motive becomes inactive right after the child gives a small push to the robot to make the robot moves.

4.2 Experiments

Because the sphere of the proof-of-concept prototype of Roball was not robust enough to be used in very tough interplay situations or for prolonged uses, tests were done in monitored conditions and with a small number of children. Each child is a unique individual that has his or her own way of interacting with a toy: this may depend on age, interest, personality, physical abilities, etc. We did not take all of these aspects into considerations by studying children's interests, psychological profiles or their evolution over a period of time, by doing a special screening of the children, by comparing Roball with a full range of other toys, or by adapting Roball's programming to the child. Our intention with these first experiments is only to see how children interact with Roball in various conditions, and more specifically observe the effects created by purposeful movements of a robot operating in the real world in the kinds of interplay situations that can emerge from interacting with children.

4.2.1 Remi and Alexis, 3 years old boys

This section describes observations made when Roball was presented to two boys of about 3 years of age, Remi and Alexis, in separate occasions.

Fig. 6. Remi, a 3 years old boy playing with Roball on a carpet floor.

Remi got to play with Roball in a room that had carpet and furniture. A small basketball of about the size of the robot was also placed in the room. Roball had no difficulty moving on the carpet. Remi is a very active boy, always trying out new things. When he saw Roball for the first time, he immediately went to play with it. Remi understood that Roball had to stay on the floor to move, so he started to follow the robot around, going where Roball was going (like under tables, in between furniture, etc.). He also played with Roball by throwing the basketball at the back of the robot, again showing the need for robustness. Remi was also able to understand Roball, and his first reflex was to talk back to the robot, giving it commands and asking it why it was behaving in particular ways. At one point the robot stopped and since Remi was not getting an answer from Roball, he started to shout his requests to the robot. He knew the robot was able to talk, and expected it to understand what he was saying. In this case, speech interaction seems to be important to create even more interesting interplay situations.

Alexis played with Roball in a household garage, on a concrete floor with a small slope toward a drain located at the center of the garage. Roball did not experience any problem moving around the garage, over and away from the drain, and even sometimes going outside on the pavement. In opposition to Remi, Alexis is calm and shy, so the first contact with

Fig. 7. Alexis playing with Roball in a garage.

Roball was very different. Initially, Alexis stood outside of the garage, looking at Roball and analyzing it from a distance. Alexis was not scared: he was looking at the robot, smiling. He was very intrigued by the fact that Roball was moving on its own. Alexis was used to play with a remote controlled car, and he did not understand how Roball was moving on its own. The fact that Roball talked was also something new to him, and Alexis sometimes repeated to his father what Roball was saying, explaining what the robot was doing. After a couple of minutes and a bit of reassurance from his father (who went near Roball), Alexis also went to play with Roball, as shown in Figure 7. He then frequently played with the robot by letting it pass under his legs. Alexis also responded to Roball's requests for spinning, shaking or pushing. Contrary to Remi, Alexis was always very gentle with the robot. For instance, Roball barely made one turn the first time Alexis made it spin. At one point Alexis' father took Roball when it was not moving, and because the *Straight* behavior was making the internal counterweight move in small increment, the father said to Alexis that he could feel Roball's heart beating. So various types of interpretation can emerge from the behavior of the robot.

4.2.2 Simon, from 10 to 30 months of age

A number of trials were done with a boy named Simon, from the time he was 10 months old. At this age, Simon had never played with a ball and he was barely crawling or being able to stand up on his own, lifting himself up by grabbing on to things. Also, Simon was not able to understand any verbal commands from the robot, so interactions with Roball were mostly caused by its movements. We first placed Roball in Simon's play pen while Simon was outside of it. Simon immediately crawled toward the play pen, and lifted himself to go inside (when he usually wanted to get out of it). Then we took Roball out of the play pen and let it move freely in the living room, the dining room and the kitchen. As the robot started to move, Simon immediately started to crawl to catch it. When he finally did, Simon tried to grab the robot and immobilize it but could not. Roball was always trying to move and every time Simon lost his grip, the robot started to move again in the released direction. Figure 8 illustrates Simon playing with Roball. This catch-and-grab cycle repeated itself a couple of times, as Roball got to move on wooden floor and ceramic, underneath a table and chairs, on the side of a couch, furniture and walls. Simon did not seem to get tired of trying to catch it or of watching Roball move. Just having Roball wander around in the room made Simon want to follow it, also making him practice his crawling and moving skills. After about 30 minutes, the experiment ended when we stopped the robot, which necessarily made Simon very upset. To observe Simon's behavior with other ball-shaped toys, we gave Simon a small basketball the next day. Simon went to grab the ball, played with it for about 30 seconds, and went away to play with other toys. We also gave Simon a small train that can move on the floor, and Simon most often grabbed the toy, threw it on the side and left it there. When the toy train is on the side or in front of an obstacle, it continues to move its wheels, just making a lot of noise until somebody decides to turn it off. Roball, on the other hand, is more versatile and pleasing in that regard because it is capable of moving purposefully (without getting stuck somewhere) in the environment.

Four months later, we let Simon play with Roball again. He then knew how to play with a ball, so he was now trying to lift Roball to throw it on the floor, showing again that robustness of the sphere is very important. But still, Simon continuously pursued Roball

Fig. 8. 10 months old Simon playing with Roball.

in the room as the robot moved on its own. With the basketball, Simon only threw it once or twice, and started to play with other toys. Interactions were again mostly generated by the movement of the robot, since Simon was still in the process of developing his language skill.

We did another trial when Simon was 21 months old, placing Roball in Simon's room. Again, Simon was very fascinated by the robot. The game he played with Roball was to try to make it stay under his crib, as shown in Figure 9. When the robot was not moving, Simon was able to succeed. But as Roball started to move again, Simon had to move fast to try to make the robot stay under his crib. Simon smiled and laughed frequently, really enjoying the interactions.

Now at 30 months old, Simon is still interested in Roball. He is now able to understand better the requests made by Roball for spinning, shaking and pushing. He likes the toy greatly, hugging Roball and telling it that he likes it, which is something that Simon started to do with Roball and that he only did with stuffed animals. He also likes to talk to Roball, explaining different things happening in his life to it. This differs from the pretend games that Simon plays with small figurines. It is as if Roball is an entity of its own, and even though the first prototype of Roball is not used anymore and is now placed on a shelf, Simon always express his happiness when he sees Roball. But on one aspect, Roball is no different than regular toys in that eventually the child's interest toward the

Fig. 9. Simon at 21 months of age trying to make Roball stay underneath his crib.

toy changes. Now that Simon is older, his interest toward Roball is not as high as in the beginning, in the sense that even though he still wants to play with Roball, he does not play as long as when he was younger. However, using Roball as a robotic toy surely has brought new and interesting interactions at different stages during the development of this young child.

4.2.3 Children with Autism

A robot toy can be used for more than entertainment: it can also serve as a pedagogical tool. One interesting idea is to use robots to help children with autism. Different projects have recently started to study the use of robotic toys for autistic children (Dautenhahn 1999; 2000; Werry & Dautenhahn 1999; Michaud *et al.* 2000a; 2000b; Michaud & Theberge-Turmel 2002). A robot toy may help autistic children open up to their surroundings, improve their imagination and try to break repetitive patterns. Speech recognition is not necessary, but generating short vocal commands can be quite useful in getting the attention of the child. The robustness of the toy is also of prime importance, since it cannot be assumed that the child will be very careful with the high tech toy. For example, when we brought a standard three-wheeled robot, the first thing one child did

Fig. 10. Rolling game with Roball.

was to try to take it all apart. Roball is protected against that, and can interact with the child using vocal messages.

So we also used Roball with autistic children, and again each child had his or her own distinct way of interacting with the robot. Some remained seated on the floor, looking at the robot and touching it when it came close to them, lifting it and making it spin (but not always when requested by Roball though). One girl liked to keep contact with the robot, but not necessarily look at it all the time. A boy, who did not interact much with almost all of the other mobile robotic toys presented to him, went by himself play with Roball. One of the game he played was to make the robot roll on the floor between his arms, as shown in Figure 10, and eventually let it go forward by itself. Others moved around Roball, sometime showing signs of excitation. While it may be difficult to generalize the results of these experiments, we can say that Roball surely caught the attention of the children, even making them smile.

5. Discussion

Even though experimental results obtained in this first cycle of the spiral design process are only qualitative, they support three important aspects that justify the continuation of the project. First, Roball reveals to be an interesting mobile robotic platform to be used as a toy. It shows robustness in facing a great variety of situations like operation on different surfaces, facing obstacles of different shapes and interactions of all sorts with children. Second, its dynamics creates interesting new interplay situations with children. Third, autonomous and purposeful movement of the robot is an appealing factor for children. Research on theory of the mind, i.e., theory on how we can understand the actions and expressions of others within an intentional or goal-directed framework (Scassellati 2000), provides an explanation on why the autonomous behavior of Roball is an appealing factor for children. Baron-Cohen's model of theory of mind suggests that one basic form of perceptual information is based on self-propelled motion of stimuli (Baron-Cohen 1995). Basic movements of approach and avoidance are represented, and a distinction is made between animate and inanimate objects. Baron-Cohen states that this mechanism is something that infants are born with. A similar view is presented in (Premack & Premack 1995). The basic unit in their theory of human social competence identifies self-propelled movements in space and interprets them as intentional and goal-directed, such as escaping from confinement, making contact with another intentional object, overcoming gravity, etc. (Dautenhahn 2000). The capability of identifying intentional autonomous movement explains how children, as early as a couple months old like Simon, might find particular interest in a self-propelled toy such as Roball. This contributes directly to the life-like nature of the toy, and the special interactions that emerged with children.

From these observations, we have identified additional considerations for the design a new prototype in a second design cycle:

- The use of a more rigid spherical shell. This would make Roball more robust to though interplay situations.
- Add sensors and actuators to create new types of interactions with children. For instance, a rotation actuator like the one used by Cyclops (Chemel, Mutschler, & Schempf 1999) can also be attached to the internal plateau of Roball to make it turn on itself autonomously.
- Give Roball the capability to adapt its behavior over time to generate more sophisticated interactions and unpredictable situations that can help capture and retain the child's interest.
- Conduct experiments to characterize quantitatively A) the locomotion capabilities of

the robotic platform (e.g., controllability, capability to mount over obstacles, navigation over incline surfaces, etc.) and B) child-robot interaction. The observations made with the proof-of-concept prototype clearly outline the worth and benefit of initiating a multidisciplinary project involving researchers in education and psychology to study the impacts of an autonomous mobile robotic toy on children.

6. Summary, Conclusion and Future Works

The conditions a mobile robot must face in a household environment are very diversified, and being also a toy for children is even more demanding. We may design a robot expecting children to play with it in an appropriate manner, while in practice it may not be the case. A real dog mistreated by a child will indicate its discomfort by barking or by moving away (and hopefully not by biting). But this may not yet be the case for robotic toys. Toy robots must then be very robust while still being able to create interesting and safe interplay situations with the child. This presents important challenges for the research community, with great marketing opportunities. In this paper we argue and demonstrate how Roball, a spherical rolling robot, is a simple solution that addresses these considerations. Roball's design allows it to handle the variety of situations that arise in a household environment, to be extremely robust and be appealing to children by being able to move autonomously in the world.

Another interesting aspect is that it is possible to exploit the physical structure of the robot, its dynamics and its control to create interactions particular to Roball. The spinning interaction with the robot is a good example of this property, which help establish the belief that the robot is actually playing and not simply executing a program. Observations made of children playing with Roball confirm that purposeful movements of the robot, its physical structure and locomotion dynamics can lead to interesting new games influenced by the environmental settings and the child's character.

Future work involves developing a new prototype of Roball, allowing us to conduct more experiments with children of different ages and for prolonged usage of the robot, and acquire more quantitative results to evaluate how Roball makes an interesting autonomous toy robot. While the number of sales can give an indication of the success of a toy, this measure is also influenced by marketing, and potential investors usually need such assessments before commercializing the product. Measures like the mean time before failure, the average time a child plays with the toy (during the day and over the years), also compared to the selling price, would be useful. Qualitative evaluations of the ability of the toy in making the child learn news things and minimize disturbances in the household (like continuous talking or moving when nobody is playing with the toy) are also important. These factors are more useful since they combine child's interest and parents' concerns, allowing the toy to be appreciated by all. Finally, all of these considerations demonstrate that artificial intelligence and autonomous robots research can benefit greatly from the field of entertainment, using it as an experimental setup for developing innovative ways of making physical machines interact intelligently in real life situations.

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Author's Biography

François Michaud is a Canada Research Chairholder in Autonomous Mobile Robots and Intelligent Systems, and an Associate Professor at the Department of Electrical Engineering and Computer Engineering of the Université de Sherbrooke. He is the principal investigator of LABORIUS, a research laboratory on mobile robotics and intelligent systems working on applying AI methodologies in the design of intelligent autonomous systems that can assist humans in everyday lives. His research interests are architectural methodologies for intelligent decision making, autonomous mobile robotics, social robotics, robot learning and intelligent systems. He received his bachelors degree, Masters degree and Ph.D. degree in Electrical Engineering from the Université de Sherbrooke. He is a member of IEEE, AAAI and OIQ (Ordre des ingénieurs du Québec).

Serge Caron is technician in computer systems at the Department of Electrical Engineering and Computer Engineering of the Université de Sherbrooke. His interests are in designing mobile robotic platforms, from four-legged to wheeled robots. He is also a writer for hobbyist robotic journals.

Fig. 11. F. Michaud

Fig. 12. S. Caron

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