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# Robots: Assistive technologies for play, learning and cognitive development

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**Abstract**. Robots have been widely used in rehabilitation. Among the various applications, robots have been developed to assist children with motor disabilities in play and academic activities. Several studies have shown the efficacy of these robotic tools, not only for allowing children to actively participate in the activities, with direct impact on the development of their cognitive, social, and linguistic skills, but also as a means to assess children's understanding of cognitive concepts, when standard tests cannot be used due to physical or language limitations. In this paper the use of robots for assistive play is reviewed from the perspectives of rehabilitation engineering and robot design, aiming at defining a set of desirable characteristics for such robots. Commercially available robots are then surveyed in comparison to the defined characteristics to evaluate to what extent they can be used as assistive robots for play, learning and cognitive development.

Keywords: Assistive robotics, play, cognitive development assessment, augmentative communication

## 1. Introduction

During typical development children learn cognitive, social, motor and linguistic skills through manipulation of objects, often in the context of play. Because of motor limitations manipulation of objects may be difficult, and the quality of play and learning of skills may be compromised [51]. Robots can facilitate discovery and enhance opportunities for play, learning and cognitive development in children who have motor disabilities [7]. The usage of robots in play contexts can also help to track changes in cognitive development by the child, and may contribute to improved cognitive understanding [13]. Success with robot tasks could be an alternative way for children to demonstrate their understanding of cognitive concepts avoiding the limitations of standardized test administration, such as verbal response or physical manipulation of objects.

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This paper begins with a brief overview of robotic systems, and then describes a series of applications to rehabilitation, focusing particularly on robots to reveal cognitive skills for children with disabilities. The results of these and other studies demonstrate the positive impact of the use of robotic systems by children who have disabilities and justify consideration of the design requirements for a robot specifically for this population. Combined with our previous experience [12,13,59] in evaluating and developing cognitive skills in children with disabilities through the use of robots, this material forms the basis for a desired set of robot characteristics for play and education applications. In the final section of the paper a review of commercially available robots based on that set of characteristics is discussed.

## 2. Robotic systems

A robot is defined as "An automatically controlled, reprogrammable, multipurpose, manipulator programmable in three or more axes, which may be either fixed in place or mobile for use in industrial automation applications." (International standard ISO 8373). Although this definition emphasizes manipulators for industrial applications, robots can assume different shapes and are widely used in other areas including rehabilitation, the amelioration of physical sensory and cognitive limitations in children and adults with disabilities. Robots can be programmed to exhibit different levels of autonomy with respect to the user. In one extreme, the robot can accept high level commands specifying a task to be accomplished (e.g., get milk glass), and be able to perform that task making whatever decisions are necessary without requesting any human intervention (fully autonomous). At the other end of the scale, the user has direct control over the robot movements (teleoperated). Multiple controls are then necessary to operate the various robot degrees of freedom. These controls might be directly or indirectly accessible (e.g., through a scanning method). For example, to position a robotic arm end-effector in Cartesian space, controls for x, y, z coordinates must be available. Between these two extremes of autonomy (autonomous and teleoperated robot), several levels of autonomy, shown in Table 1, can be defined, Sheridan's scale [63] being the most widely cited. One of the most commonly used levels in assistive robots is level 4 of autonomy, in which the user merely needs to hit or press and hold a switch to replay a pre-stored movement.

Robots can be roughly divided into the following fundamental components (e.g., [56]): Chassis and Energy, Propulsion and Actuators, Environmental Interface, Navigation, Guidance and Control, Communications, and Mission Control (see Fig. 1). Robots can be mobile or stationary. The following description is for mobile robots, but with the necessary adaptations to each component description, the diagram in Fig. 1 can also be applied to stationary robots.

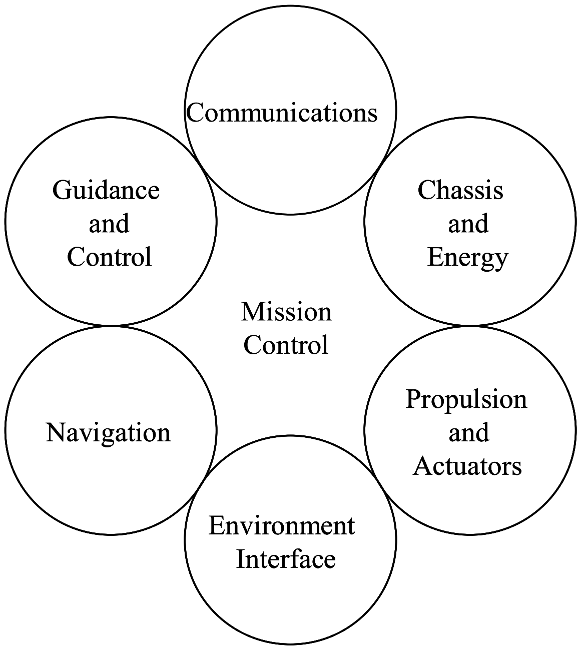



Fig. 1. Fundamental robot components.

*Chassis and Energy* refers to the structural part of the robot and to the power system on board, usually made of rechargeable batteries. The *Chassis* defines the robot shape and relates to the mechanical robustness of the robot and payload capabilities. It should be adapted to the environment where the robot will be used (e.g., indoor or outdoor).

The *Propulsion and Actuators* component is responsible for robot movement. It encompasses the motors and the actuators that transform motor rotational movement into translational robot movement. Actuators can be wheels, drive tracks or artificial legs. The type and geometry of the actuators influences the way a robot can move. It can be holonomic, meaning that all degrees of freedom are controllable, or it can be non-holonomic, only being able to control some of the degrees of freedom. Automobiles are usually non-holonomic since the user can only accelerate/brake and change the angle of the steering wheel in order to control the vehicle three degrees of freedom (x, y position and orientation). The vehicle cannot be moved sideways, for example. However, omni-directional wheels can provide sideways control and an additional degree of freedom. Usually actuators are equipped with odometers that measure the distance traveled by the vehicle (e.g., wheels usually have encoders that give the number of revolutions of the wheel since it started to move). This information, together with wheel radius is sufficient to estimate the distance traveled).

In order to perceive the environment and physically act on it the robot must include an *Environmental interface* component: sensing and manipulation. Sensors can be active, providing the energy necessary for information acquisition, or passive, measuring only available energy. Examples of active sensors are range-finding sensors like sonar or laser beams. Bumpers (touch), or force sensors are passive. Video cameras may have both passive (e.g. image sensor) and active (e.g. auto-focus system) elements. Robotic arms or some kind of gripper can be added to a mobile robot to enable physical manipulation of the environment, like picking up an object. Often these manipulation tasks require that the robot be able to detect and recognize

Table 1
Sheridan's levels of robotic autonomy (Sheridan and Verplank, 1978)

| | |
|---|---|
| 1. | Computer offers no assistance; human does it all. |
| 2. | Computer offers a complete set of action alternatives. |
| 3. | Computer narrows the selection down to a few choices. |
| 4. | Computer suggests a single action. |
| 5. | Computer executes that action if human approves. |
| 6. | Computer allows the human limited time to veto before automatic execution. |
| 7. | Computer executes automatically then necessarily informs the human. |
| 8. | Computer informs human after automatic execution only if human asks. |
| 9. | Computer informs human after automatic execution only if it decides to. |
| 10. | Computer decides everything and acts autonomously, ignoring the human. |

objects in the environment through an appropriate sensory system. For example, force sensors may help to efficiently grasp an object. Also, depending on the robot sensory systems, safety issues aimed at protecting the robot, the environment, and the user (e.g. avoid falling down stairs or hitting obstacles) may be implemented.

*Navigation* systems provide current linear and angular positions and vehicle velocities. The position can be known relative to an initial position (using odometer readings), in relation to obstacles (using range-finding sensors) or in a global coordinate frame (absolute position obtained by a Global Positioning System (GPS) or by comparing range-finding measures with a map of the environment). Some localization methods resort to landmarks placed in the environment which are detected by the robot sensory system. Techniques used for object detection and recognition (e.g. using RFID[1] tags on objects) are also used for customizing the environment for robot use. Modifying the environment and objects so they can "communicate" with the robot is usually referred as ubiquitous computing or embedded intelligence. Maps of the environment can be known a priori or can be interactively built by the robot as it moves around.

After knowing where the robot is, it is necessary to know where to go and how to get there. First *guidance systems* define a target point; then *control laws* drive the vehicle from the current position to the target point. Modern control strategies integrate guidance and control, guaranteeing stability and performance of the combined system.

The *Communications* component encompasses visual and auditory feedback to the user and also the communication systems, if any, that convey information on the robot state or sensory information to a base station. Visual feedback can be provided by means of a display or simply by meaningful use of indicator lights; auditory feedback can be either sounds, playback of prerecorded messages or text-to-speech generation. Currently, wireless communication systems are standard.

Finally, the *Mission Control* component accepts high level commands from a program or from a user directly to specify a given task and coordinates all the components so the robot can execute the task. Therefore, it encompasses the human-robot interface and the software necessary for subsystem control. This software must be able to coordinate several concurrent processes to achieve a particular goal, and it is usually designed under Artificial Intelligence or Hybrid Systems[2] frameworks. The human-robot interface should match the robot user needs. Most probably the robot will be used by non-technical persons thus an intuitive control language should be developed, preferably a graphical one or possibly natural speech. The human-robot interface may also have additional features depending on the characteristics of the users, e.g. children with disabilities.

It is at the mission control level that different levels of autonomy are implemented. Table 2 indicates the degree of sensing, feedback and controllability that the robot must have for each of Sheridan's ten levels of autonomy. Controllability refers to the complexity of the control unit used to obtain robot movement ranging from one button, to a sub-set of functions, to controls for all the degrees of freedom. There are some grey areas between categories in the table. For example, although one could argue that a robot with level one of autonomy (teleoperated) need not be programmable, in order to implement several levels of autonomy in the same system the robot should be fully programmable. Table 2 is a guide to the characteristics that are necessary or desirable for a robot to have in order to function at a given level of autonomy. Thus, typical assistive robots operating at level 4, must have range, cliff, touch

[1] Radio Frequency Identification.

[2] Hybrid systems are those that include continuous and discrete states.

Table 2

Hardware/software necessary to implement each of Sheridan's levels of autonomy

| Level of Autonomy | | Sensing | | | | | Feedback | | | | | Controllability | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Contact | | | Visual | | Auditory | | | | | |
| | | Range finding | Ciff | Touch | Force | Image | Lights | Display | Recorded message | Speech Synthesis | Sound | Controls for all DOF | Sub-set of controls | Single control |
| 1 | Computer offers no assistance; human does it all. | | ≈ | ≈ | | | ≈ | | | | ≈ | × | | |
| 2 | Computer offers a complete set of action alternatives. | | ≈ | ≈ | | | ≈ | | | | ≈ | | √ | √ |
| 3 | Computer narrows the selection down to a few choices. | × | × | × | ≈ | × | ≈ | √ | √ | √ | ≈ | | ≈ | × |
| 4 | Computer suggests a single action. | × | × | × | ≈ | × | ≈ | √ | √ | √ | ≈ | | ≈ | × |
| 5 | Computer executes that action if human approves. | × | × | × | ≈ | × | ≈ | √ | √ | √ | ≈ | | ≈ | × |
| 6 | Computer allows the human limited time to veto before automatic execution. | × | × | × | ≈ | × | ≈ | √ | √ | √ | ≈ | | | × |
| 7 | Computer executes automatically then necessarily informs the human. | × | × | × | ≈ | × | ≈ | √ | √ | √ | ≈ | | | × |
| 8 | Computer informs human after automatic execution only if human asks. | × | × | × | ≈ | × | ≈ | √ | √ | √ | ≈ | | ≈ | × |
| 9 | Computer informs human after automatic execution only if it decides to. | × | × | × | ≈ | × | ≈ | √ | √ | √ | ≈ | | | × |
| 10 | Computer decides everything and acts autonomously, ignoring the human. | × | × | × | ≈ | × | ≈ | | | | ≈ | | | × |

Legend: × Must have; ≈ Convenient; √ One of the items marked must be available.

and image sensing to keep from getting into inoperable situations (e.g., falling off of a table) and they must have either visual display or auditory message (preferably both) as feedback to the user/programmer.

## 3. Robots to support therapy, activities and participation

Robotic systems have been widely applied to rehabilitation. Several applications are for children and are described in the next sections. Upper extremity prostheses and exoskeletons are beyond the scope of this paper. Section 4 describes robotic applications to reveal cognitive skills for children with disabilities. The most important and relevant robotic system components from each rehabilitation application will be discussed in Section 4.5.

### *3.1. Robots for physical therapy*

The rationale behind applying robots to physical therapy is that "robot-aids not only are more efficient in delivering certain routine physical and occupational therapy activities, but also provide a rich stream of data that assists in patient diagnosis, customization of the therapy, and maintenance of patient records (at the clinic and at home)." [38]. Rehabilitation robots are typically stationary and have articulating parts that guide the child through required movements with control over resistance, speed, and number of repetitions (e.g. [37]). Exploring the plasticity of the brain, the goal oriented repetitive movements that the robots are able to induce may contribute to the re-learning of the movement by the patient, while saving physical and occupational therapists' time. The Lokomat, a robotic assisted treadmill, has been used therapeutically to improve gait speed, endurance and standing and walking performance in children with cerebral palsy [8,36,47].

### *3.2. Robots as personal assistants*

The goal of applications with robots as personal assistants is to provide manipulation aids to people with motor impairments and or intellectual disabilities, assisting with several everyday functions such as eating or personal hygiene [14]. Personal assistants can be robotic arms which can be stand alone assistive technologies (see e.g. [68] or integrated in a wheelchair [62]). More recently, mobile autonomous platforms with and without robotic arms have been developed to assist elderly and people with disabilities in their homes (see e.g. [16, 55,50]).

### *3.3. Assistive mobility*

Robotic systems have been applied in assistive mobility to develop power wheelchairs (see e.g. [14], chapter 12, and the references therein) with environment sensors and control systems that enable these wheelchairs to become more autonomous (e.g. [52]). Research has been carried out to design mobile robots that young children can use [10,73].

### *3.4. Robots for social integration*

With the development of the Artificial Intelligence research field, new kind of robots showing aspects of human-style intelligence has emerged. These socially interactive robots are able, to some extent, to perceive and interact with their environment, and have been used to promote social integration. Several studies have been conducted to establish the usefulness of robots in autism therapy. People with autism have impaired social interaction, social communication, and social imagination [18]. Robots could be helpful when human intervention is a barrier to learning, as might be the case with autistic children. Also, it is hypothesized that the "social" relationship the autistic child might develop with the robot can then be transferred to humans. Both stationary robots which imitate human face expressions and gestures, and mobile robots that interact with children trough movement have been developed. Please refer to [18,49]. For a survey on socially interactive robots see [21]. Recently, research has been done addressing the more general problem of developing robots that can be children's partners or playmates (e.g. [32,7]).

### *3.5. Using robots to aid functioning by children with disabilities*

The pioneering work of Seymour Papert [57] showed that robots can enhance motivation and provide a test bed for "learning by doing". For children with disabilities, robots can provide a means to engage in play and academic activities that involve the exploration and manipulation of the environment [12]. Robots have been used successfully to allow children to participate in school-based tasks that would otherwise be closed to them. A prototype interactive robotic device was used for play by two groups of children, four in pre-school (2 to 4 years old) and five in elementary school (5 to 9 years old), all having moderate to severe physical impairments, and five also with cognitive delays [33, 42,43] adapted the Manus arm for use by children with cerebral palsy (CP) by altering both the physical control of the robot and the cognitive tasks required for control. The robot was used for various pick and place academic activities with six participants, 7 to 29 years old, all of whom had CP. The Handy 1 Robot, originally designed as a feeding aid, was adapted for use in a drawing task to allow children to complete assignments with minimal assistance in class alongside peers [64]. A specially designed robot for access to science lab activities was trialed with seven students aged 9 to 11 years who had physical disabilities [28]. Access to the science and art curricula for students, aged 10 to 18 years, who had arthrogryposis, muscular dystrophy, and CP was evaluated with a multi-purpose workstation called the ArlynArm [19]. Harwin et al. [25] describe a robot workstation for use in Education of the physically limited based on the low-cost commercial SCARA robot. Clinical trials with the SCARA involving stacking and knocking down toy bricks, sorting articles, and playing the Tower of Hanoi game, showed that the children enjoyed using the robot and were able to achieve tasks otherwise impossible for them. In the PlayROB project [40] a dedicated robot system which supports children with severe physical impairments for interaction with Lego bricks was developed. A first set of trials was conducted with three able-bodied children (between 5 and 7 years old) and three disabled children (between 9 and 11 years old; child 1 – multiple disabilities; child 2 – tetra paresis; child 3 – transverse spinal cord syndrome). According to the authors, “In general, most of the children enjoyed playing with the system and the goal to make autonomous play for children with physical disabilities possible has been fully achieved.” (page 2899). Upgraded versions of the robot system were then used in a multi-centre study involving children with and without disabilities to investigate possible and estimated learning effects. The encouraging results of this study are reported in [40]. Tsotos et al. [69] present a research project aiming at building a robotic system to access and manipulate toys. The focus of the research in this project has been on the vision system because that’s the greatest technical challenge in the authors’ opinion. The problems faced by children with mobility impairments were addressed in the initial stages of the project (see e.g. [5]).

All the above applications in this section use robots as therapeutic or enabling tools. However, as stressed in Section 1, observing children using robots can also provide a means to assess their cognitive development. Section 4 is dedicated to robots for manipulation which are used in scenarios designed to test children’s demonstration/development of cognitive skills.

## 4. Using robots to reveal cognitive skills for children with disabilities

The potential of using robots to reveal cognitive skills for children with disabilities has been referred to by other authors (e.g. [23,71]). Research projects in our group (see references 1–4, 11–15, 59, 65) have focused on cognitive skills associated with robot use in three ways. First, robot studies have been designed to require specific cognitive skills by the child. Generally, constrained in some way, these investigations have revealed underlying cognitive skills that may have been undetected or not easily measured by more traditional means. Second, environments of discovery have been developed in which children with disabilities are encouraged to explore and problem solve using robots. These unconstrained studies have provided a platform on which children can demonstrate a variety of cognitive skills. Finally, there have been studies of robot use by young typically developing children. Three of the robots used in these studies are shown in Fig. 2.

### *4.1. Means end causality and tool use by infants*

Infants typically develop the concept of tool use in which they understand the relationship between objects and use one object to obtain another (e.g., using a stick to extend reach to push a toy) by age 8 months [70]. In order to determine if this concept would also apply to the use of a robot, the MiniMover robot arm (Fig. 2) was used with young children with and without disabilities aged 6–18 months in a direct control task in one dimension [11]. The MiniMover is a half human scale robotic arm with six degrees of freedom (shoulder, elbow, wrist and base rotation, and wrist flexion and extension). It is designed for table top use in an open loop control mode. The robot arm held a cracker. When the child pressed a switch the arm moved it closer, and when the child released the switch the arm stopped moving. Reaching for the cracker and then pressing the switch when the cracker was out of range was taken to mean the child was using the robot as a tool to bring the cracker closer. This conclusion was also supported by observed behaviors such as point of visual regard (e.g., looking at the arm, then looking at the switch, then pressing the switch, then looking back at the arm expecting it to move) and affect (smiling, crying, laughing to indicate level of enjoyment or distress) during task [11]. The use of behavioral analysis such as this has also been reported by Dautenhaun and Werry [17] who called them “micro-behaviors”. Three

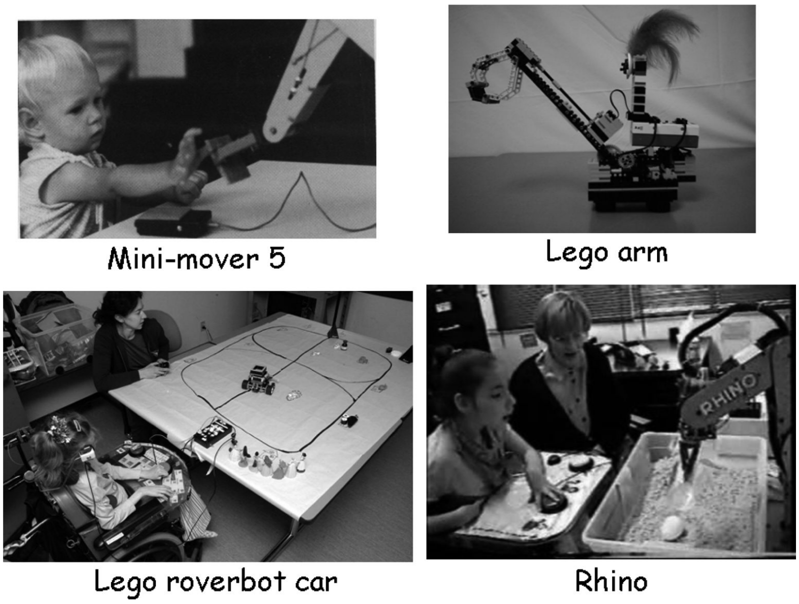



Fig. 2. Robots used in studies with children who have disabilities.

typically developing and six developmentally delayed children participated in the study in a pre-school setting. An infant development scale (Bayley Developmental Scale) was used to asses the cognitive age of the children [6]. All typically developing children whose age was greater than eight months used the robot arm as a tool and younger children did not. All children with disabilities who had a cognitive age greater than eight months also used the arm as tool.

### *4.2. Sequencing in a constrained task*

In order to evaluate the ability of young children to carry out a three step sequencing task, the Rhino robot, shown in Fig. 2, was used by twelve children 5–10 years old who had severe physical disabilities [12]. The Rhino robot is an industrial robotic arm with the same degrees of freedom of the MiniMover. It is also designed for table top use but has built in closed loop control systems for each joint and can also be controlled in Cartesian space coordinates. Children controlled the robot using single-switches. None of the participants were able to engage independently or with another child or adult without some adaptation in co-operative play in which objects of various materials (e.g., sand, water, macaroni)" are placed in containers of various types and then dumped out for the sensory (auditory, tactile and visual) feedback that occurs. All of the participants had experience using single switches to operate toys and to access computer games, but for many of the children, consistent switch access was generally not established, and it was difficult to assess cognitive and language skills using standardized measures. A large tub of dry macaroni noodles was used as the medium for burying objects. There were three tasks for the child. The first task involved pressing switch 1 to cause the robot to dump the macaroni from a glass. The second task had two switches each controlling one step: (1) press switch 2 to dig an object out of the macaroni, and (2) switch 1 to dump the macaroni and object. The third task consisted of a three step procedure for the child: (1) press a 3rd switch to position the robot arm for digging (using up to 8 increments of movement requiring multiple presses of the switch), (2) press the switch 2 to dig an object out of the macaroni, and (3) press the switch 1 to dump the macaroni and object.

Goal Attainment Scaling (GAS) [35] was used to evaluate the participants' level of achievement in these three tasks. Five levels were assigned: expected result (value $= 0$), two better performance levels ($+1$, $+2$) and two worse ($-1$, $-2$). Examples of GAS Scales are shown in Table 3.

All twelve of the participants were able to independently control at least two switches in the sequence. Seven of the children independently used all three switches and one used three switches with some prompting. Teachers initially thought that the researchers had overestimated the skills of the children in selecting them for this project. At the end of the study, teachers were surprised at the level of accomplishment

Table 3
Examples of goals used in goal attainment scaling

| | Goal attainment scaling guide | | |
|---|---|---|---|
| Goal | Operation | Functional | Carry over |
| +2 Best Expected Outcome | Controls 3 switches with auditory and visual prompts | Understands "your turn" and responds appropriately | Unexpected gains in classroom activities |
| +1 Better Than Expected Outcome | Controls 2 switches with a 2 step scoop with out assistance | Understands turn taking with auditory and visual prompts | Shows more interest in classroom activities. Eg. Increase in vocalization, words, attention span, and enthusiasm |
| 0 Expected Outcome | Controls 2 switches intentionally with out assistance | Anticipates and responds accordingly to her turn | Increased interaction, and becomes excited when teacher speaks about the robot session |
| −1 Less Than Expected Outcome | Controls 2 switches with prompting | Anticipates the outcome of the task | No change |
| −2 Worst Expected Outcome | Controls one switch intentionally | Enjoys interaction with the instructor during the trial | Shows less attention, is more passive in the classroom, and anticipates session when she sees the therapy staff |

of the children. A set of open-ended questions were also used with the teachers to provide insight into child's social and academic performance before and after using the robot. The primary themes from the teachers were:

Reactions:

– "[student] Smiled and got excited when robot mentioned in class or at home."
– "Robot gave [student] something to look forward to and become excited about."
– Children's reactions to robot were very positive
– Robot tasks were more motivational (generated more interest and excitement) than single switch tasks with toys, appliances and computer-based activities

Communication:

– "had more vocalizations in class, and was more interactive after robot use."
– "[Student] used new symbols in class and interaction increased."

Confidence

– "[student's] confidence and interaction increased, he looked forward to the sessions."
– "On the way to robot [student] anticipated what was going to happen; her ability to control robot increased [student's] self esteem."

This study is reported in more depth in [12].

### *4.3. Discovery and problem solving in unconstrained tasks*

In the previous two studies [12,13] the tasks were constrained due to the nature of the robots and the type of control required. The robots were also expensive ($1500 to $10,000US), making replication in schools and children's home difficult. Lego MindStorms[3] robots cost approximately $300US and provide a very flexible platform for evaluating how children use robots. Namely, one can easily build robots with different shapes, stationary or mobile. Small motors may be used for propulsion or to drive moving parts. Several sensors (e.g. touch, light, sound) are available to provide information about the environment. These robots are equipped with a microprocessor that allows for programming different levels of autonomy. Additionally, they can be remotely controlled via infrared signals. For our studies, the commercial remote controller was adapted to enable the control of the robots using single-switches. The Lego Invention[4] "roverbot" vehicle and robotic arm (Fig. 2) were used to determine if low cost robots could provide a means by which children with severe disabilities can demonstrate understanding of cognitive concepts [13]. Both constrained and uncon-

[3] http://mindstorms.lego.com/en-us/default.aspx.
[4] http://mindstorms.lego.com/.

Table 4
Robot skills related to development of cognitive skills. (From [13]

| | Skill | Definition for robot use | Age considerations* (typically developing children) | Lego Robot Examples |
|---|---|---|---|---|
| 0 | No interaction | Child displays no interest in the robot or its actions | NA | NA |
| 1 | Causality | Understanding the relationship between a switch and a resulting effect | $<$ 3 action is in switch, tried to use disconnected switches $>$ 4 yrs understood switch made robot move | Use switch to drive robot, knocking over blocks with robot, drawing circles on paper by holding a switch down and turning robot |
| 2 | Negation | An action can be negated by its opposite | 4 yrs: begin to understand that switch release stops robot | Releasing switch to stop robot |
| 3 | Binary Logic | Two opposite effects such as on and not on | 5–6 yrs: understood 2 switches with opposite effects. | 2 switches turning robot right/left, or go and stop |
| 4 | Coordination of multiple variable Spatial concepts-multiple dimension | Movement in more than one dimension to meet a functional goal | age 5: Could fine tune a movement by reversing to compensate for overshoot, etc | Moving roverbot to a specific location in two dimensions |
| 5 | Symbolic Play | Make believe with real, miniature or imaginary props [51] | 6 yrs: Child ID action in robot not switch, planning of tasks is possible | Interactive play with pretense, i.e. serving at tea party, exchanging toys with friends , pretending to feed animals all using robot |
| 6 | Problem solving | Problem solving with a plan – not trial and error, Generation of multiple possible solutions | 7 yrs. Designed robot and thought about coordinated effects, planning was possible, Can understand simple programs and debug | Changing strategies to solve a problem such as avoid an obstacle, Changing task to meet the child's own goal, simple programming |

From Forman (1986).

strained tasks were utilized in a study with different levels of autonomy that allowed free play and discovery by ten participants who ranged in age from four to ten. Their disabilities were primarily cerebral palsy and related motor conditions with widely variable motor, cognitive and language abilities. All had complex communication needs and were non-speaking.

Initially, participants used single switch activation to activate pre-stored movements such as a robot dancing, knocking over a stack of blocks or drawing circles on a large piece of paper. This established that the child had an understanding of causality and the function of the switch in controlling the robot. For participants who demonstrated understanding of robot control, four switches were used in an unconstrained discovery task in which the child controlled the roverbot to turn (left/right) and move (go/stop). For some children the switches were accessed with hand movement and for others it was a combination of hand and head movement.

In order to characterize and evaluate the cognitive skills being demonstrated by the participants during the unconstrained use of the robot, a comparison to robot use by typically developing children was used. In a study of three to seven year olds using a *Robotix*™ robot[5] construction kit, children demonstrated five problem solving skills: causality, spatial relations, binary logic, the coordination of multiple variables, and reflectivity [22]. The specific robot skills achieved in each of these areas varied with the age of the children. Stanger and Cook [65] studied typically developing children, one to three years of age, using a Hero 2000 robot[6] in a series of increasingly cognitively complex tasks. Cognitive skills investigated included causality and the use of sequencing two and three switches to carry out a task. Two and three year old children consistently demonstrated causality, while the youngest children (16 months) were inconsistent in this task. Only the three year old children were able to complete the two step sequencing task. None of the children completed the three step sequence successfully. Based on these studies of typical children's use of robots, the set of robot tasks shown in Table 4 was developed. Each task requires cognitive skills of varying levels of complexity. A child's performance on these tasks, which are progressively more cognitively chal-

[5] Robotix discontinued, but see http://en.wikipedia.org/wiki/Robotix_(toys).

[6] Hero 2000 discontinued, but see http://www.hero2000robots.com/9501.html.

lenging, provides a proxy measure of cognitive understanding by children with disabilities performing robot tasks by comparison to typically developing children at different ages. The results of the study involving ten children with disabilities is summarized in Table 4 and reported in more depth in [13].

In a recent study, eighteen typically developing children aged three, four and five years used a Lego robot to complete tasks based on the cognitive concepts of causality, negation, binary logic and sequencing [59]. All of the participants understood causality. The four and five year old children grasped the concept of negation, but the three year olds had more difficulty understanding this concept. Most of the 4 and 5 year old participants succeeded at the binary logic (left and right) task. Forman found that only children older than four were able to understand binary logic. This may have been due to Forman's use of one rocker switch with two directions of movement whereas this study used two separate switches for each direction located spatially on the left and right side of the forward switch. None of the three year olds were able to consistently use a two step sequence to accomplish a task. Four year olds displayed greater understanding of the sequencing task than younger children, while five year olds had no problem in accomplishing the task. This study verified that the cognitive skills listed in Table 4 develop at the ages shown for typical children.

### *4.4. Integrating communication and robotic manipulation*

Children who have motor limitations are sometimes also limited in communication. These children may use Speech Generating Devices (SGDs) to meet some of their communication needs. SGDs are stand alone or computer based electronic devices that produce digitized or speech output in response to selections made by the child using a variety of input methods including typing, head pointing or scanning [14]. One of the challenges faced by these children is the degree to which use of the SGD isolates them from other activities including play and academics. For example, an SGD is generally placed directly in front of the child and the child has to turn away from it in order to play. Since much of play and selected portions of the academic curriculum involve manipulation of real objects, integrated systems have been developed so children can communicate and control Lego robots using the same device and access method. Many SGDs have the capability to learn infrared commands, for instance to control televisions and DVD machines. Since the Lego Mindstorm robots are infrared controlled, they can be controlled from SGDs. New generation of Lego Mindstorms and SGD have Bluetooth capability, but that version has not been tested to date.

Using communication devices to control the Lego robots addressed several limitations observed in previous Lego robotic play studies. For example, it can be difficult to find the six switch access sites required for control of a three degree of freedom robotic arm for children with severe motor disabilities, and several participants could only use single or dual switches. Thus, using their communication device, these children are able to control the robot via scanning. In addition to scanning, the use of an augmentative and alternative communication (AAC) device opens up the possibility of other alternative access strategies such as manipulation of a cursor through head or eye pointing. Hence, the main difference in the robotic system from the previous Lego robot studies was in the Human-Robot Interface.

Two pilot studies of an integrated system have been undertaken [1,15]. In the first study, an integrated communication and robotic play testing platform underwent usability testing and iterative design with professional experts [15] and children with and without disabilities (in preparation). The experts and older children (5 years old) were able to teleoperate the roverbot, but the younger children (3 years old) were only able to control the robot by pressing one switch to initiate a program of a sequence of movements. The results showed that children prefer to do activities using the robot rather than directing another person to do it and that they will spontaneously talk using the communication device during play. The testing platform provided a means to examine the best ways to present information (pages, links, symbols) for finger-pointing users, but requires testing with scanning users.

In the second study, a commercially available communication device was used by a single participant (a 12 year old girl who has Cerebral Palsy and uses two switch scanning) to examine the feasibility of controlling Lego robots for academic activities [1,2,4]. This study was useful to establish that it is feasible to control Lego robots via an AAC device for social studies and math activities. With systems such as these, children can demonstrate and develop manipulative, communicative and cognitive skills in an integrated way.

### *4.5. Robot system components for rehabilitation applications*

The robot system components shown in Fig. 1 have unique properties in each of the rehabilitation applications discussed in this and the previous sections. For example, in the case of robots for physical therapy, as personal assistants or to provide assistive mobility, the *Chassis and Energy* component should be specifically designed for its intended use. For other rehabilitation applications, since payloads are generally small and the robots are generally used in indoor controlled environments, the *Chassis and Energy* and *Propulsion and actuators* components do not provide major design challenges. *Communications* generally takes the form of feedback to the user regarding the task and the status of the robot. Most pediatric applications in rehabilitation have limited communication with the child, but they may have significant communication with a user interface remotely accessing the robot for the researcher/therapist/caretaker. This component is also often employed to download programmed tasks into the robot. The level of autonomy (Table 1) has a direct effect on the *Environmental Interface, Navigation*, and *Guidance and Control* robot system components. The greater the autonomy, the more dependence there is on the design and implementation of these elements. For most of the applications described here, these components play a small role. The exceptions are robots used as personal assistants, modern assistive mobility devices, or robots for social integration where these components become more important. The *Mission Control* component is essential for defining and executing particular tasks in a variety of rehabilitation settings. Since it encompasses the human-robot interface, particular attention should be dedicated to this component so the robot can be easily used by a broad range of persons, with and without disabilities (e.g. therapists, caretakers). If the intended users are persons with special needs, appropriate accessible control interfaces and selection methods should be considered (see [14], chapter 7, for a discussion on human-robot interface for persons with disabilities).

## 5. Characterization of assistive robots for playing and cognitive assessment

Commercially available robots were applied in the research using robots to reveal cognitive skills described in the previous section. Most of the components in Fig. 1 were already implemented and appropriate for the applications. The only customization necessary was modification of the Mission Control System in order to provide accessible control interfaces for children with special needs and programs to carry out the specified tasks. However, the use of commercially available robots poses limitations on the various play and education scenarios where robots could be useful for children with disabilities. For example, the large and robust Rhino robot[7] was expensive and required specialized programming. The small but inexpensive Lego robots[8] were fragile and required frequent minor adjustments. Small robots also have limited payloads and cannot be implemented for functional tasks with actual play or academic objects. Limited environmental sensing and navigation capabilities may limit the degree of autonomy that can be achieved. Often the Mission Control component is limited to simple commands or short programmed tasks and not suited for more complex scenarios such as automatic adjustment of the degree of autonomy according to the child's performance. Based on a literature review conducted by the authors in 2008 and on the experience gathered from previous robot studies, the desired characteristics of a robot specifically designed for assistive manipulation in play and school by children who have disabilities are discussed in this section. Literature on design of socially interactive robots and manipulation aids for adults was also surveyed and the concepts that were consistent with our play and education goals were also included. Kemp et al. [34] give an overview of the present challenges in developing robots that perform useful work in everyday settings.

### *5.1. Design considerations for a children's robot*

The main considerations in designing a robot for assistive play and education are: intended use, technological characteristics, aesthetics, and economic considerations (Fig. 3).

#### *5.1.1. Intended use*

As described by the Human Activity Assistive Technology (HAAT) model [14], the design of any assistive technology system should start by defining the Activities in which the user needs/wants to engage and the Contexts in which those activities will take place.

[7] http://www.rhinorobotics.com/.
[8] http://mindstorms.lego.com/.

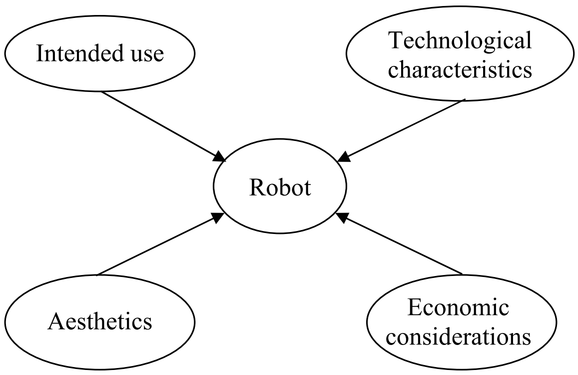



Fig. 3. Robot design forces.

In the present case, the activity is robot-assisted manipulation that allows children with motor disabilities to engage in play and academic activities providing a tool for exploring, discovering and altering the environment. Ideally the robot will be flexible enough to allow for a wide range of activities. Activities should be developed only by considering user needs and preferences, not by constraints of any specific technological solution [60]. The third aspect of the HAAT model approach is a consideration of the skills the person is capable of for participating directly in the activity and for controlling the interface to the robot. The envisioned activities, contexts and anticipated human skills should then determine the required technological capabilities and characteristics of the robot.

*5.1.2. Technological characteristics*

A desired robot characteristic is robustness [29,41, 49]. A robot that is robust will also be more reliable. When working with children who have disabilities, the need for reliable and accurate robots is essential since failures frustrate and disengage users [12,26,30, 39,41]. Also, robot inaccuracies in performing a given task must be compensated by human intervention, thus limiting independent use of the system by the child. Robustness issues should be taken into consideration when designing each of the robot components shown in Fig. 1.

Safety is a key issue when designing robotic systems to be used by children [29,30,39,44,48,49,53]. The robot cannot, in any situation, place the child in danger. Moreover, "the acceptance of robots for health-care applications has been slowed by safety concerns" [44, p. 298]. Lees and LePage [44] also discuss the tradeoff between cost and safety. Michaud et al. [48] specifically refer to the problem of avoiding small parts. Safety has direct implications in the design of the robot chassis since it should incorporate passive elements that prevent injury to the child in case he or she comes in contact with the robot. Also the sensory system should enable the robot to detect and anticipate dangerous situations. Finally, the mission control system should implement safety procedures that override any other vehicle operation.

It is mostly at the mission control level that special attention is necessary when developing robots for children with disabilities, since this component encompasses the human-robot interface and the coordination of all robot subsystems to accomplish a specific task. Software design for robot control has its base in the Human Robot Interface (HRI) research field and is dependent on considerations from different areas of expertise such as psychology, physical and occupational therapy, speech and language pathology, artificial intelligence, and computer science. Goodrich and Schultz [24] provide a comprehensive survey of human-robot interaction. Human-robot interfaces should be intuitive and accessible for non-technical individuals [26]. The development of "standard control software to enable the use of the same programs across robotic systems" is also important [30, p. 150].

A rehabilitation robot for children should be usable by children who have a variety of disabilities, should have easily learned operation, and should include simple and comfortable access to input devices [29,44]. The interface software should provide easy, transparent access to the capabilities of the robot empowering the user and giving a sense of effective control over the system and environment [29]. Additionally, the robot should interact in a natural manner with the user and robotic systems, operation should be easily learned by non-technical users and children [49] and provide appropriate feedback. Kronreif and Prazak-Aram [41] aimed at "plug & play" operation for their robotic system. Teaching the robot through the child's own body motion is a natural way for children to program the robot [58]. However, teaching by the child's movement is more directed to socially interactive robots or physical therapy than to assistive robots for children who have motor disabilities to augment physical movement of objects.

In principle, the HRI should provide full control over the assistive technology (e.g., allowing all degrees of freedom of a mobile robot to be controlled) so the user can be fully in charge of the activity. In practice, due to motor or cognitive impairments, it might be necessary for a portion of the control to be taken over by the robotic system (e.g. Levels 2–10 of Table 1). This may limit the freedom of the child (e.g., to move the robot from one point to another the user might only be able to select pre-specified destinations using a scanning method and the system would plan the trajectory and drive the robot through that trajectory, avoiding obstacles if they occur). Progressing through levels of autonomy (e.g., from Level 10 to Level 4 or 5 of Table 1) allows for the gradual introduction of the control of the assistive technology. Decisions to move from one level to another can be based on skills such as those shown in Table 4 since each higher level in Table 4 requires greater autonomy by the child and less by the robotic system. The robotic system should then have a high degree of autonomy in the first trials, but can gradually release control to the user as he or she masters the system. If possible, after the learning process, the user should be able to fully control the robotic system (Level 1). Thus, software that allows for the implementation of different levels of autonomy that match the child's performance level must be developed. Ideally the robot would automatically adapt its level of autonomy according to user performance. Several authors report the use of different levels of autonomy in their robotic systems (cf. [10, 13,25,27,29,53]). Some of these robotic systems offer more than one level of autonomy, but none of them automatically adapt. Future development of robotic systems that automatically adapt the level of autonomy according to user performance would increase the ability of the robot to help the child develop autonomy as skills increased.

For a discussion on the user interface for an assistive robot based on considerations from robotics, cognitive science, human factors engineering, and human-computer interaction fields, please refer to [66]. Most important concepts to a successful human-robot interface design, like visibility (of the controls), conceptual mapping (between the controls and the actions), feedback, modeless interaction, and error recovery or reversible actions, are common to the design of everyday things [54,66]. Stanger's paper also addresses the evaluation of specific interface designs, stressing the importance of involving the user in the design loop at early stages.

Other desirable technological characteristics for a child's robot include: portability, so the robotic system can be used in a place the child knows, thus reducing distractions and anxiety [26,53,72]; availability of a logging system to record every play session in order to assess possible learning effects from the robot use [40]; and usage of vision sensors, essential to enable self adaption of the robot to changes in the environment [25, 44].

#### *5.1.3. Aesthetics*

Robotic systems for children must be appealing to the child and significant others [28]. Aesthetics in the design of assistive technologies for children has been studied for augmentative communication devices and robots separately.

Light et al. [45] examined popular toys for young children to identify potential designs that might improve the appeal of AAC systems. Recognizing that current AAC devices are designed by adults, Light et al. [46] conducted a study in which six children without disabilities were asked to design low-tech AAC prototype systems to obtain an indication of the children's preferences. The children's inventions differed significantly from the designs of current AAC technologies, namely they incorporated multiple functions (e.g., communication, social interaction, companionship, play, artistic expression, telecommunications), provided dynamic contexts to support social interactions with others, and made use of bright colors, lights, transformable shapes, popular themes, humor, and amazing accomplishments to capture interest, enhance appeal, build self-esteem, and establish a positive social image [46]. The AAC systems designed were seen as children's companions and were easily personalized to reflect the user's age, personality, attitude, interests, and preferences.

Bumby and Dautenhahn [9] conducted a study with thirty eight children between the ages of seven and eleven, divided in groups of nine to ten, to identify how they perceived robots and what type of behavior they may exhibit when interacting with robots. It was found that children see robots as having geometric forms with human features in their faces and feet for walking, placed them in familiar settings and social contexts, and attributed free will to them. Despite the familiarity with the technology all groups showed a tendency to overestimate the capabilities of the robots. The robots should be appealing to attract children's attention [12, 49,61,67]. Examples of ways to make robots appealing to children are the use of bright colors, replication of well known children's themes (e.g., cartoon or book characters), incorporating amusing movements or actions, and allowing for easy personalization to match the child's preferences. Balance must be obtained between creating an attractive robot and distracting the child from the tasks by too many cosmetic features. These considerations have impact on the design of the chassis and communications components of the robot.

#### *5.1.4. Economic considerations*

Along with safety, cost is one of the most frequent limitations of rehabilitation robots cited in the literature [20,26,30,31,39,44]. There is a cost-performance tradeoff, industrial-grade robots are robost but expensive and cheaper robots designed for education are inexpensive but not robust. Two observations found in the literature are: "poor cost-to-performance ratios have been the major weakness of the 'functional aid' applications for robotic/mechatronic systems" [20, p. 24], and "in education, professionals have concentrated on finding ways of forcing cheap robots to barely meet their needs rather than developing robotic systems that are truly well suited for educational purposes" [44, p. 298]. In fact, cost is still the limiting factor in developing robots for children who have disabilities that can be widely used in school or home scenarios.

### *5.2. Characteristics of commercially available robots*

A web based survey of commercially available robots was carried out by the authors in 2009 in order to compare available technology with the desired robot characteristics. Ready-to-operate robots, kit robotic systems, and mobile platforms designed for educational robotics development were surveyed. Search criteria, reflecting those characteristics we considered fundamental to the robot were:

a) Mobile robots with manipulation capabilities or with the option of adding manipulation capabilities, to allow for a wide range of play activities;
b) Dimensions compatible with table play activities so it is possible to use the robot in different play contexts (school or home) while seated in a wheelchair or supportive seating system;
c) Wireless and omnidirectional user robot interface to avoid cables and "shadow" control zones where the robot looses communication with the user interface;
d) Cost less than 600 Canadian dollars. This constraint is included in order to make the robot widely available.

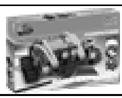
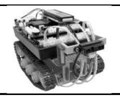
A graphic programming language is desirable so non-technical persons, including children, who have disabilities can program the robot.

Table 5 presents the best candidates among the robots considered. Prices are based on the web search and thus are approximate. In order to operate every robot listed it is necessary to program it first. All robots have a potential payload of at least 200 gr. All systems require the design of a customized human-robot interface to make them accessible to children with special needs. If a particular robot accepts commands via infrared signals, off the shelf assistive technology devices can be used to control the robot such as switches, communication devices or a computer. New assistive technology devices incorporate Bluetooth technology thus also allowing for the control of robots that accept commands via Bluetooth.

Table 5 characterizes each robot and relates it to the robot components shown in Fig. 1. Additional detail has been added to some of the component categories shown in Fig. 1. Due to the cost constraint, only Mindstorms NXT from Lego or Robot Explorer from Fischertechnik (first two robot columns of Table 5) meet the design specifications without any additional technical development at the robot level. The previous Lego studies reported on earlier in this paper were conducted with the earlier infrared controlled Lego Mindstorms robot, not the currently available Bluetooth version shown in Table 5. A wide range of sensors comes with these systems and the manufacturers provide a visual programming environment usable by non-technical persons, including children. Various robot configurations can be built with the kits, allowing for some customization. Also, being a mass product designed for children, they are appealing, easy to operate, and documentation and parts are readily available. Assuming the child will not have the opportunity to disassemble the robot and come into contact with small robot pieces, these robots do not raise any safety issues. Drawbacks of these systems include robustness and reliability. Robots built out of these kits are fragile and usually do not perform consistently due to construction weaknesses (e.g., gears can easily get misaligned). Most of these "technical" problems can easily be solved by non-technical helpers, e.g. peers or caretakers. However, these problems can be both confusing and frustrating to the child and can reduce their independence.

Robot columns three to eight of Table 5 list educational robotic systems or mobile platforms that require some mechanical/electronic development in order to meet the robot design specifications. In all, no intervention is needed in the Chassis and Energy components and the open hardware architecture allows for hardware customization. All but the Protobot Kit from VEX robotics require the addition of manipulation capabilities. A set of sensors is provided with every listed robot, but additional sensors may be needed. Sensors can be easily added by a technical developer resorting to off-the-shelf kits (see e.g. www.phidgets.com). An

Table 5
Commercially available robots

| Robot / Charact. | | Mindstorms NXT LEGO | Robot Explorer Fischertechnik | Protobot Kit VEX Robotics | iRobot Create | A4WD1 Robot Lynxmotion | Arobot-P1 Arrick Robotics | Interactive C Robot Kit V2.0 Inex Robotics | IntelliBrain-Bot Ridge Soft |
|---|---|---|---|---|---|---|---|---|---|
| Cost CAD | | $350,00 | $312,50 | $500,00 | $287,50 | $525,00 | $500,00 | $370,50 | $550,00 |
| Mission control - Human-robot inertface | Programming requirements | Non-technical | Non-technical | Non-technical | Expert | Expert | Expert | Expert | Expert |
| | Operational requirements | Non-technical | Non-technical | Informed user | Informed user | Informed user | Informed user | Informed user | Informed user |
| | Robot remote control | Bluetooth remote control using appropriate software | | | IR Remote control | | | | |
| Environment Interface | | Light, sound, range-finding (sonar) and touch sensors | Odometers, negative temperature coefficient resistor, photoresistor, sonar, color sensor, track sensor | Limit switch, bumper switch, robotic arm | Cliff and touch sensors, wheel drops, distance traveled, angle displacement, omnidirectional IR sensor (for commands or Virtual Walls) | 3 obstacle detection sensors | Odometers | Switch-IR reflector, wheel encoders | Line sensor, range-finding sensors (IR and sonar), 2 infrared photoreflector sensors |
| Communications | | Loudspeaker, display | 3 ligths, buzzer | | Lights (LEDs, function programmable), speaker (possible to record up to 16 sequences of notes) | | Lights (LEDs, function programmable), sound output transducer | Piezo speaker | 16x2 LCD |
| Chassis | Operation | Assembling necessary | Assembling necessary | Assembling necessary | | Assembling necessary | Assembling necessary | Assembling necessary | Assembling necessary |
| | Structure configuration | Variable | Variable | Fixed | Fixed | Fixed | Fixed | Variable | Fixed |
| | Size | 20x15x20cm | Not available | 43.2x31.4x20cm (arm all the way down pointing forward) | 33cm diameter | 27.9x31.8x12cm | 25.4x25.4x12.5cm | base plate: 16x6cm | Not available |
| | Weight | ~350gr | Not available | Not available | 2.9kg | 1.8kg | 1kg | Not available | Not available |
| Accessories | | | RF Data Link ($200,00), ROBO Interface (microprocessor) ($250,00), ROBO Pro Software ($37,50), ROBO I/O extension ($150,00), Control Set (joystick remote control), Sound + Lights package, Motor sets | Transmitter & Receiver kit to allow human operator control ($162.50) | Home base ($87.50), remote control ($31.25), virtual walls ($50.00), light sensor ($10.00 for two) | IR Proximity detector ($37.50), tracker line sensor ($25.00), IR detector ($18.75), range-finding (sonar) sensor ($45.00), touch sensor ($12.50), accelerometer ($31.00), force sensing resistor ($6.25), gripper kit ($90.00), remote controller ($25.00) | Upper deck ($72.50), Expansion kit (light sensor, pyroelectric infrared motion sensor, temperature sensor and mechanical parts) ($68.75) | Sound detection, metal detection, color selection, piezo speaker, tilt sensor, LED output, infrared detector, switch input, temperature sensor, magnetic field sensor, light detector, CMUCAM2 vision system (prices not available) | |
| Picture | |  |  |  |  |  |  |  |  |
| Manufacturer link | | mindstorms.lego.com | www.fischertechnik.com | www.vexrobotics.com | store.irobot.com | www.lynxmotion.com | www.arrickrobotics.com | www.inexglobal.com | www.ridgesoft.com |

interesting accessory is available for iRobot Create: it is an infrared beam emitter that creates a virtual wall that the robot will not cross. That can be used to limit the robot workspace, providing an extra safety feature. Excluding the case of iRobot Create, these robots are not widely available and thus the probability of product discontinuation and after-sale support should be carefully assessed. Although the necessity of customization always raises final product robustness and reliability issues, the educational robotic systems have the potential of performing more consistently over time. If well designed, namely the human-robot interface, they can be as easy to operate and program as the Lego or Fischertechnik systems.

Table 5 shows that there are no commercially available robots that are 100% suitable for use by children with disabilities. All described robotic systems require a specific HRI for these children. This can either be a commercial product (e.g. Big Jack from Gewa)[9] or adaptation of the standard human-robot interface [12]. IROMEC (http://www.iromec.org, accessed in February 3, 2009) is an example of a project aiming at development of a robotic system specifically designed for children with disabilities.

In summary, robotic systems based on Lego or Fischertechnik building blocks can be successfully used as assistive technology devices for assistive play. Being widely available at a reasonable price and being easy to operate by non-technical users, it is conceivable that parents and schools may provide them to their children for long term use. However, it is necessary to adapt the hand held remote controller so people with disabilities can use it. The human-robot interface for the Lego or Fischertechnik robots can be built from commercially available devices thus not preventing children with special needs from using them. Taking advantage of the international communities around Lego or Fischertechnik, multiple research groups can write robot programs and building instructions and make them available over the internet.

## 6. Conclusions

There are several general results that have been noted in all of the studies related to cognitive function and development described above. One of the most important is that overall teachers' and parents' perception of the competence of the children increased after successful use of the robots. Universally, the children enjoyed using the robots and anticipated the robot sessions. The use of robots also gave the children a chance to demonstrate a range of cognitive skills while also providing a versatile tool for presentation of tasks, problems and learning opportunities to the child. The insight into cognitive skills provided by the use of the robotic system provides a means of avoiding the limitations of standardized test administration, such as verbal response or physical manipulation of objects. Integration of communication and robot control in play and education activities enhances participation and interest for the child and is effective in providing a means for children to demonstrate integrated manipulative, communicative and cognitive skills. The success of these studies stresses the importance of children to have access to Assistive Robots for assistive play and education. The characterization of rehabilitation robotic systems provides a framework for the consideration of the suitability of commercially available robots for use by children who have disabilities. The Mindstorms NXT from Lego or the Robot Explorer from Fischertechnik may meet the needs of rehabilitation applications, but further development in the area of assistive robots is needed to address the limitations of these commercial devices.

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