Development of a robotic device for facilitating learning by children who have severe disabilities

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Development of a Robotic Device for Facilitating Learning by Children Who Have Severe Disabilities

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***Abstract*—This paper presents technical aspects of a robot manipulator developed to facilitate learning by young children who are generally unable to grasp objects or speak. The severity of these physical disabilities also limits assessment of their cognitive and language skills and abilities. The CRS robot manipulator was adapted for use by children who have disabilities. Our emphasis is on the technical control aspects of the development of an interface and communication environment between the child and the robot arm. The system is designed so that each child has user control and control procedures that are individually adapted. Control interfaces include large push buttons, keyboards, laser pointer, and head-controlled switches. Preliminary results have shown that young children who have severe disabilities can use the robotic arm system to complete functional play-related tasks. Developed software allows the child to accomplish a series of multistep tasks by activating one or more single switches. Through a single switch press the child can replay a series of preprogrammed movements that have a development sequence. Children using this system engaged in three-step sequential activities and were highly responsive to the robotic tasks. This was in marked contrast to other interventions using toys and computer games.**

***Index Terms*—Assistive technologies, computer-assisted learning in children with disabilities, physical disabilities, play and disabilities, rehabilitation robotics.**

I. INTRODUCTION

THE purpose of this paper is to describe the development of a robot arm system that facilitates learning by children who have severe physical disabilities. Applications of this and similar systems with children who have disabilities have been described elsewhere [1]–[5]. Children with disabilities have the same needs to explore their environment as a means to academic and cognitive growth as do typically developing children. For children with disabilities, the ability to independently manipulate objects or move about their environment can be very limited. This can also limit the ability to engage in discovery through typical play activities. To compensate for limited grasping and manipulative ability, battery-powered toys, simple electronic aids to daily living (EADLs) that allow single switch control over appliances such as blenders and computers adapted to allow access by the child have been widely used [see [6], for example]. Switches that are activated by gross body movements are often used to control these toys and programs. However, toys are limited to a few functions and children often lose interest in them relatively quickly. Computer-mediated play ranges from simple cause and effect programs to more complex programs requiring children to make decisions and engage in more difficult control of the software. However, computer activities are two-dimensional (2-D).

Rehabilitation robotics is concerned broadly with the development of robotic aids to assist people who have a manipulative disability to complete tasks of daily living [7]. In contrast, the robotic system described here was developed to investigate the degree to which independent manipulation of three-dimensional (3-D) objects by a child with a severe disability can be achieved and the impact of that independent manipulation on the child's cognitive and language development. We are interested in the relative value of robotic movements used for 3-D exploration since these movements simulate manipulation by typically developing children [8]. Since manipulation of objects is a key element in the development of cognitive and language skills, robotic devices have the potential to play a key role in the growth of independence and the development of cognitive skills for severely physically disabled children who lack the ability to grasp and manipulate objects. Robotic systems provide an opportunity for them to manipulate real objects and discover their properties. Children with severe movement disabilities have great difficulty engaging in activities that generate tactile, auditory and visual feedback as a result of the child's interaction with an object. Their reduced exposure to this form of play may restrict their development of motor coordination and perceptual and cognitive development.

There are two primary technical challenges in the development of robotic systems for use by children who have severe multiple disabilities: 1) physical demands of the control interface and corresponding and skills of the child and 2) cognitive understanding required for operating the system and the corresponding problem-solving skills of the child. For this reason our development has focused on the user interface between the child and the robotic system. Generally, in assistive technology applications, there is a tradeoff between physical and cognitive demands placed on the user. The simplest cognitive task is one in which there is a one-to-one correspondence between the task and the control interface used by the child. For example, complete movements may be stored and replayed by a child with a single switch press. Alternatively, a 3-D movement would require six independent switch sites to control each dimension in two directions. Since robotic systems are flexible, a variety of tasks can be implemented in the same system. Nof, Karlan and Widmer [9] used a two level system for developing a child's

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interaction with a robotic arm. At the first level, the arm functioned to carry out complete tasks. Sublevels included by Nof, Karlan, and Widmer were one- and two-step sequences, each used to carry out the same task. At the second level, the robotic arm allowed the child to control component actions and incorporate these into more complex sequences. Howell, Damarin, and Post [10] developed a robotic system for use in elementary schools. They used a small robot, a five-position slot switch and a computer to control the arm. They defined four levels of control: 1) demonstration of the arm to the student; 2) performance of well-defined and prestored tasks; 3) unstructured movement controlled by the student; 4) student programming and storage of movements for later playback. In order to accomplish these tasks, Howell, Hay, and Rakocy [11] identified special software and hardware considerations. These include easy physical and cognitive access and fast interactional speed, understandable, powerful, and complete learner control features and the definition of the robot motions useful in the classroom. This robotic system was applied to science instruction at the elementary school level [12]. Two phases of field study were carried out: 1) a training component in which the student became familiar with the use of the robotic system; and 2) an instructional component in which the robot was used to complete science experiments. Important issues raised by this study were the need for the robot to be transparent to the user (i.e., the student can focus on the learning task not robot control), training methodology and curricular applications.

If the child lacks the ability to control several switches or keys then scanning is typically employed [13]. This is generally more cognitively demanding than the direct selection method described above. For example, Kwee and Quaedackers [14] used single switch scanning to select the direction of movement and then activation of the switch by the child to control arm movement. Significant training was required to understand the cognitive aspects involved in the tasks (e.g., pouring water from a glass, eating a cookie). Smith and Topping [15] allowed children with severe disabilities to draw with a robotic arm. A scanning selection by the child was used to choose the pen color and position (up or down-to draw). Single switch scanning moved the pen to draw. A wide range of success in the three subjects was reported. Cook, Liu, and Hosseit [2] evaluated whether very young children would interact with a robotic arm using a small custom modified and computer-controlled robotic arm [1]. All of the children with a cognitive developmental age of 7 to 9 months or greater used the arm as a tool to obtain objects out of reach. Success in using the robotic arm was most closely related to developmental levels in cognitive and language areas [3].

The organization of the paper is as follows. Section II describes our methods. Section III discusses the technical aspects of our experimental robot system. Section IV describes the experimental results of our pilot study with children who have disabilities. Section V discusses our results and the last section concludes the paper.

II. METHODS

A. Design Approach

The user interface determines the relationship between the child's motor action to activate a control interface (e.g., a switch) and the robotic system control methodology. Selection of control interfaces for a specific child is determined through an evaluation by therapists and teachers for a specific user [13]. The robotic system can interface different types of user controls and make them accessible to each individual user. Designing an intuitive and efficient user interface that allows a child with severe disabilities to use a sophisticated robotic manipulator is the primary goal of the work reported here. To accommodate for the variety of childrens' needs and skills, we designed the user interface and robotic system in general to be flexible and to provide a variety of options in both cognitive and physical skill requirement for operation. At the most basic cognitive level, simple preprogrammed tasks are "re-played" by the child activating one or more switches. Two- and 3-D movements activated directly by separate switch pairs for each dimension or indirectly through single-switch scanning. Finally, independent joint movements can be utilized through a set of 7 switch pairs to explore more complex 3-D problem solving tasks. This robot system also serves as an assessment "probe" that can provide data regarding problem-solving abilities, physical skill, and understanding of cognitive tasks such as sequencing. The system we have developed is a research tool. The robotic system described here has served as a test bed for development and testing of concepts related to the impact of independent manipulation on physical and cognitive development. Concepts evaluated here have been transferred to other smaller and less sophisticated systems for use in the school environment. Its use may help to define the specifications for less expensive and more portable robot is for use in schools and one or our goals is to define this set of operational specifications through a series of studies in the laboratory and in the school setting.

B. Pilot Study Methods

In our study, the children remain seated in their own wheelchairs, with the robot manipulator mounted in front of them [4]. The evaluation of the system was carried out at the Glenrose Rehabilitation Hospital in Edmonton, Alberta, Canada. The system was programmed to: 1) carry out preprogrammed movements when activated by a switch closure; 2) to execute 3-D Cartesian coordinate movements when activated by one of six switches or keyboard keys; and 3) to move any of the six degrees of freedom and open or close the gripper when one of 14 switches or keyboard keys was pressed. The keyboard function allowed the use of enlarged keyboards that reduced the physical demands for high-resolution movements by the child. Scanning selection in was used to select the desired action by one single switch activation through scanning and then executing the movement by a second switch activation.

The preprogrammed tasks were based on concepts characteristic of children's play activities [4]. Some children could not use their hands for the control of the robot arm due to paraplegia, spasticity, or athetosis as a result of cerebral palsy. In these cases, switches controlled by head movements were used. For children with severely limited fine motor control, there is limited bandwidth for communication between the child and the robotic system. This places severe constraints on the type of interaction that can occur. When controlling a robotic arm to move freely in 3-D space, the user must plan a series of movements based on their projection onto the control axes, in either robot-joint or Cartesian space. This can be frustrating and mentally challenging especially with limited experience. It is difficult for children to achieve this type of control without prior experience in manipulating objects. In order to allow children the opportunity to experience manipulation without using free movement anywhere in the workspace of the robot, we designed the user interface and robot control software to build on small preprogrammed moments to develop the child's level of understanding and then a manipulation strategy that allows the child to generate the robot's trajectory in a similar way to which humans naturally plan and execute motions using three dimensional Cartesian movements.

In our paper, we focused on container play in a large tub of dry macaroni (e.g., scooping and dumping) using a robotic arm controlled by a set of three switches activated by the child [4]. The robotic arm was programmed to carry out tasks when the child pressed one to three switches in a sequence. Three tasks were used in our initial evaluation study.

Task 1 The arm dumped macaroni from a glass using one switch-hit. The adult's role was to fill up the cup with macaroni (by hand) the child's task was to hit a switch causing the robot arm to DUMP the macaroni that the adult would catch. The child then indicated that the cup should be filled again (typically by looking at the cup).

Task 2 The child used two switches: 1) dig an object (e.g., a plastic egg with some kind of small toy inside) out of the macaroni; and 2) to dump the macaroni and object. The adult's role was to bury the egg, catch the egg when the child dumped it out, and open the egg for the child when the child requests it (e.g., by looking at the egg).

Task 3 The robot arm was positioned so that it had to be moved to the correct position for digging by the child hitting a third switch. The adult's tasks were the same as for Task 2. Once the child positioned the robotic arm, the task was identical to task 2.

Feedback of the robot movement to the child is mainly through vision. The child observes the robot manipulator movement to determine the desired end position in the horizontal plane and then stop the robot arm at that location. For preprogrammed tasks, the switch always activates the same preprogrammed task. Multiple switches to repeatedly execute the same sequence of preprogrammed tasks activate sequences of two or more tasks. Each child's session using the robotic arm was video taped for later analysis.

III. Technical Aspects of the Experimental System

In order to implement this study, it was necessary to develop a child-controlled robotic system. This was accomplished by adding functionality to a commercially available robot (CRS 465, to be discussed later). The added functionality was in two areas: 1) developing hardware and software for a user interface that was suitable for use by young children who have very limited motor control; and 2) the addition of a prosthetic hand for use as a gripper. This required that a custom electronic interface be designed to allow control of the prosthetic hand from the commercial robotic controller.

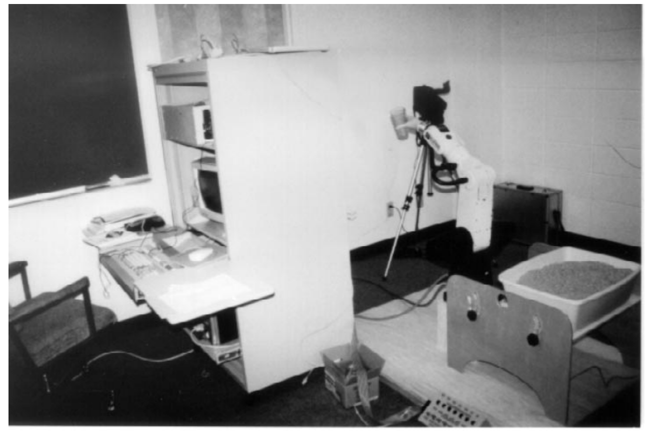

Fig. 1. The robot arm system consists of a microcomputer, the C500 controller (lower portion of cabinet on left), the robot arm, a tub of dry macaroni, and a switch interface box for connecting the child's switches (lower center).

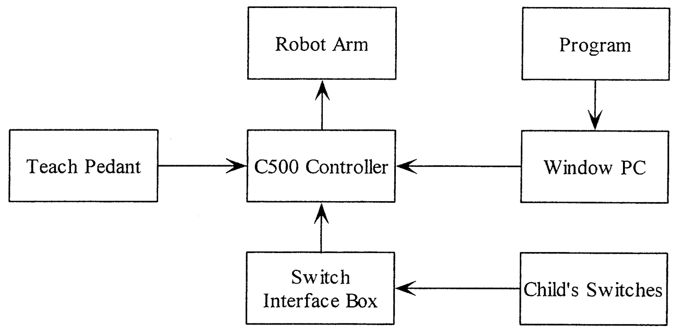

Fig. 2. Block diagram of the robot arm system.

A. The CRS Robot Manipulator

Overview of the System: Our system is based on a CRS A465 robot arm system (CRS Robotics Corporation, 5344 John Lucas Drive, Burlington, Ontario Canada L7L 6A6), a personal computer, a teaching pendant, and the GPIO (general-purpose I/O interface), as shown in Fig. 1. The computer is connected to the CRS C500 controller, via serial port and the I/O switches are connected to the controller via the GPIO port. Fig. 2 shows a block diagram of the system. The system includes the CRS A465 robot arm system, a personal computer, and an input/output interface. The computer is connected to the CRS C500 robot controller via a serial port and the child's switches are connected through a specially designed interface box to a GPIO port on the controller. The computer and robot controller also record data reflecting the tasks performed by the robot arm.

Robot: The CRS A465 robotic arm, approximately the same size as an adult human arm, can rotate about its base, flex and extend at the elbow and shoulder, extend, flex, supinate, and pronate at the wrist, and open and close the gripper. The robot arm can reach a maximum distance of 89 cm when it is fully extended. The motions are transmitted through gears and cables to each of the six joints by six separate stepper motors mounted on the robot. The use of stepper motors limits the payload of the

Fig. 3. The robot arm dumping a glass of dry macaroni.

Fig. 4. The robot hand with glove.

arm while allowing high-precision movements. With a gripper installed, it can hold a large size cup and move smoothly in its workspace. The motions are transmitted through gears and cables to each of the six joints by six separate stepper motors mounted on the robot.

Safety Considerations: The researcher, in consultation with the child's therapist or teacher decides on the specific switch arrangements and movements required by the child in order to insure that they are safe. As shown in Fig. 3, the robot arm itself is not within the reaching distance of the child nor is the child within the workspace of the robot arm. All interactions on the part of the child with the system are through switches or a head mounted mouse pointer Switch locations are selected and mounted based on the child's most functional and controllable site. The robot movement can be stopped at any time by pressing the emergency stop button of the teaching pedant. To ensure safety, the teaching pedant is held by the researcher while the child is involved in the experiment.

B. Gripper Subsystem

Gripper Mechanics: An Otto Bock myoelectric prosthetic hand covered with a latex glove is attached to the arm giving it a human-appearing three-fingered grip (Fig. 4). A custom interface was designed and built to allow the gripper to be opened and closed by the child. This makes it possible for the arm to hold a large size cup as well as small objects such as children's blocks or stacking rings. The opening distance of the gripper can be controlled through a custom interface to the robotic controller. The mechanical and electronic components of servo gripper are mounted inside the housing. The fingers can be positioned at any point between 0.9 and 5.0 cm. Regulating the current applied to the motor can control the force that the fingers use to grasp an object. When the servo gripper is installed the robot payload is 11 kg.

Gripper Control: As shown in Fig. 5, the servo gripper control system consists of three parts. These parts can be further divided into three logical blocks: 1) Servo Gripper Card-The motor driver circuit performs a digital analog conversion and provides ± 15 V dc at 500 mA to drive the motor. The torque feedback circuit buffers the feedback from the current sensor (proportional to applied torque) inside the servo gripper and performs an analog-to-digital conversion. The finger position feedback circuit buffers the feedback from the servo potentiometer circuit inside the servo gripper and performs and analog-to-digital conversion; 2) Switch—This is for systems that use an eighth servo axis instead of a servo gripper; 3) Servo gripper body—The motor is a dc permanent magnet type. During normal operation, it draws around 250 mA and up to 500 mA at the start of a motion. There is a gear rack attached to each finger platform. Finger platform position is continuously variable between 0.9 and 5.0 cm.

For position sensing of the fingers, a pinion that engages the drive racks links to a 10-k ohm servo potentiometer. The output of the potentiometer is fed into a circuit, which relates voltage to finger position. The voltage varies between 6 V dc when the fingers are fully open, to 0 V dc when they are closed.

C. Custom User Interface

The CRS robot is used throughout the world in industrial applications such as product testing, material handling, dispensing, machine loading, and assembly. It also has many applications in robotics research, educational programs, and laboratory automation. The standard CRS robot has a teaching pendant and keyboard and Windows™ interface, which are used to design the preprogrammed tasks. In our study, the standard user interface was not appropriate for use by children with severe disabilities because they could not physically use it. Therefore, a customized user interface was designed and added to the system.

Switch Box: To allow the replay of preprogrammed movements by single or multiple switch activations, a switch box was designed. We used the 14 inputs to monitor the state of the child's switches. There are a total of seven pairs of switches. Each pair includes two color-coded push button switches and two miniphone jacks. The miniphone jacks are used to connect the switches used by the child. There are seven LED lamps on the centerline of the switchbox, which indicate which pair of switches has been pressed. The switch box allows the child to play back preprogrammed movements or move the robot arm in Cartesian space by activating single switches or switch arrays. One pair of switches can be used to open and close the gripper. Each of child's switches is plugged into a minijack of the switch box and used as an interface between the child and the robot arm. Fig. 1 shows the relationship among the switchbox, the controller and the robot arm.

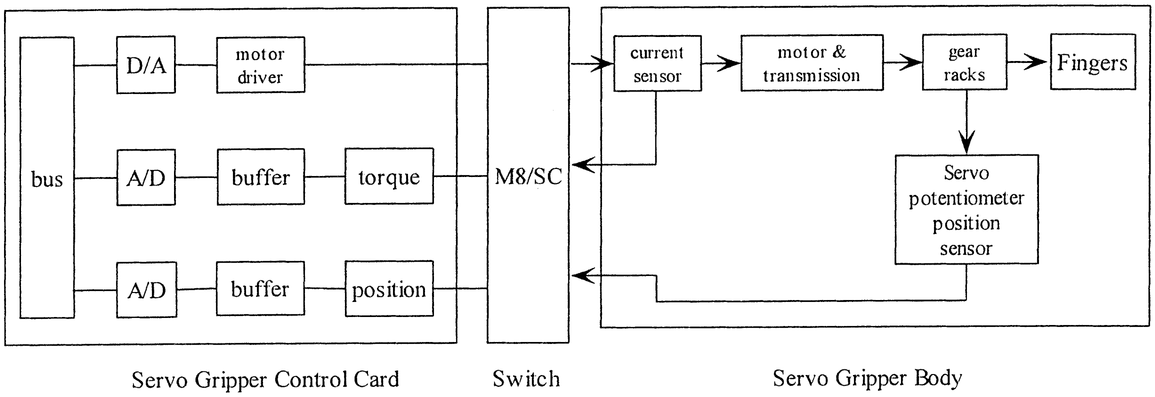

Fig. 5. Block diagram of the robot control of the gripper.

TABLE I
RELATIONSHIP BETWEEN USER SWITCHES AND JOINT CONTROL

Switch	Function	Switch	Function
1	Joint1 clockwise	8	Joint1 counter clockwise
2	Joint2 clockwise	9	Joint2 counter clockwise
3	Joint3 clockwise	10	Joint3 counter clockwise
4	Joint4 clockwise	11	Joint4 counter clockwise
5	Joint5 clockwise	12	Joint5 counter clockwise
6	Joint6 clockwise	13	Joint6 counter clockwise
7	Gripper open	14	Gripper close

Interface to the Robot Controller: There are two ports available for interfacing to the CRS C500 controller. One is the system I/O port and the other is a general purpose I/O (GPIO) port. The GPIO connector allows the C500 to control and monitor external events. The C500 has 16 isolated inputs and 16 isolated outputs. These inputs and outputs can be used to interface other devices and machines to the C500 controller, for control, monitoring, and other purposes. The switch box was connected to this GPIO connector.

D. Software

System Interface Software: The CRS robot system includes user interface software, called ROBCOMM. This software provides the communication between the user and the robot controller. The CRS robot family uses the CRS robot proprietary language known as RAPL-II, an automation-oriented, line-structured language, developed to facilitate the design of robot applications. We used the RAPL-II language to develop control programs for this application. This includes the three preprogrammed tasks. There are one-switch-based, two-switch-based, and three-switch-based tasks. For controlling the robot arm in the robot joint or the Cartesian space, up to 14-switch-based tasks may be used. The A465 Robot is programmed using CRS proprietary RAPL programming language. Programming features include continuous path, joint interpolation, point-to-point relative motions, a straight-line plus an on-line path planner to blend commanded motions in joint or straight-line mode.

User Interface Software: The IFSIG command in RAPLII is used in a conditional statement to determine the status of a selected GPIO input. As shown in Table I, each of the switches 1 to 14 of our switch box is connected to one of the GPIO inputs. This allows us to use the IFSIG to read the individual switches.

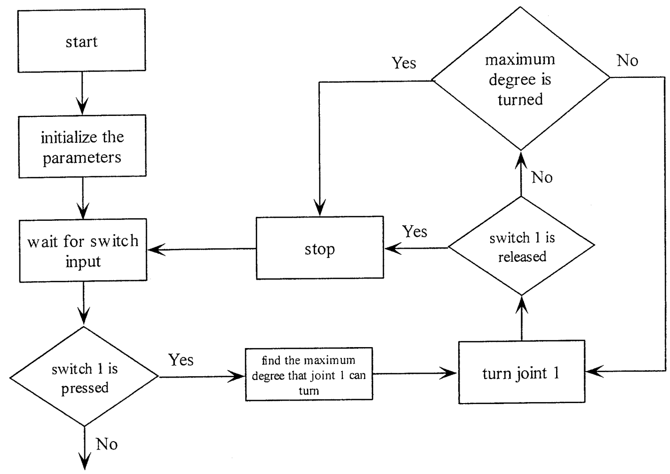

Fig. 6. Software control of individual joints by individual user interface switch pairs.

TABLE II
RELATIONSHIP BETWEEN USER SWITCHES AND 3-D CARTESIAN MOVEMENT

Switch	Function	Switch	Function
1	X increase	8	X decrease
2	Y increase	9	Y decrease
3	Z increase	10	Z decrease
4	Gripper open	11	Gripper close

To control the robot using joint control, all 14 switches are used. They are divided into seven pairs. Six pairs of the switches are used to control the reciprocal movements of the robot arm joints: base, shoulder, elbow, and wrist (3). The seventh pair is used to control the opening and closing of the gripper. This arrangement is shown in Table I.

Since each joint has a maximum range of movement, the program calculates the maximum allowable rotation before executing a movement command. Fig. 6 is a flow chart showing the program that reads switch #1 and moves joint 1. A typical RAPL command for joint movement is: *JOINT 4,80 (the fourth joint of the robot arm rotates turns 80 degrees clockwise*).

For 3-D Cartesian movements, eight switches are used. They are divided into four pairs. Three pairs of switches are used to control the robot arm movement along X, Y and Z-axes. The fourth pair is used to control opening and closing of the gripper. This relationship is shown in Table II.

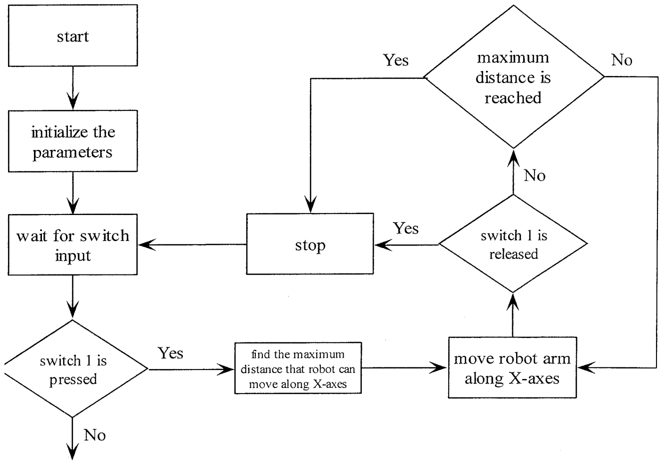

Fig. 7. Software control for Cartesian movements by individual user interface switch.

There is a work envelope in Cartesian coordinates that cannot be exceeded. Thus, the first step in the program is to determine the maximum allowable distance the robot arm can move in the chosen direction prior to executing a command to move the arm in that direction. Fig. 7 is a flow chart showing the program that reads switch #1 and moves the robot arm in the X direction. Typical Cartesian movement commands in RAPL are shown in Fig. 7.

Cartesian Movement:

$X1$ *(the robot end effector will move along the* X*-axis for 1 inch*)

$Y2$ *(the robot end effector will move along the* Y*-axis for 2 inches*)

$Z3$ *(the robot end effector will move along the* Z*-axis for 3 inches*)

E. Methods Used to Train the Robot

In addition to the joint and Cartesian control methods, the three tasks described above were implemented in our study. This required programming of the robotic system to carry out specific sequences of movements when the child activated one, two or three switches in succession. There are three different ways to program the CRS robot to execute desired movements. The first method, teach-by-text, uses text commands or program steps to program the movements of the robot. We used this approach in two ways: 1) the ROBCOMM communication and control software to run the applications written in RAPL-II; or 2) single commands in the ROBCOMM command line. Once a desired position is found and we want to store that position the text command detects and records position and orientation of the robot. The entire movement (e.g., for each of the three child's tasks) was written as a series of text commands and saved into a source file. All these source files are compiled into an application Then we can run this application to replay the functions such as dig, dump and move and so on.

The second method of training the arm is to use the teaching pedant. The teaching pedant buttons are used to direct the robot arm through a desired path. The path is then stored for later playback using the function keys on the teaching pendant or the child's switches. In our application, the teach pendant was used to fine-tune the movements, although it can also move the robotic arm over its entire range. The final method is trajectory following. In this case, the brakes of all the joints of the robot arm are released and the arm is manually moved through the desired path. The path is stored for later play back using the function keys on the teaching pendant or the child's switches. This method is the most easily used by teachers and therapists to develop movements for replay based on the combined requirements of specific classroom tasks and child's skills.

F. Playback Module

The playback module replays sets of predefined movements when the child's switches or keyboard is activated. The system was programmed to allow the child two ways to replay the robot movements. The first is called the single mode in which a single switch activation replays an entire movement. The second mode, continuous, requires the child to keep the switch pressed in order to have the playback continue. For this study, the single mode was used. Each stored source file is in the form of stored locations. During this type of control procedure, the user must plan and store a series of incremental movements based on their projections onto the available control axes, generally either in the robot joint space or the Cartesian space. Movement from location to location is executed via commands such as these:

```
 MOVE LOC1 (move the robot arm to the pre-
defined location called LOC1)
If clause:
 IF &1 = 1 THEN 100 (if the variable
equals to 1 then execute statement1)
 IF &1! = 1 THEN 101 (if the variable
does not equal to 1 then execute state-
ment2)
100 statement1
101 statement2
```

The conditional statements are related to switch activations as in Fig. 8. The source files compiled during an application constitute a stored movement database. The three primary tasks (dump, dig, and move) are each part of this database. The database also included movements such as retrieving an object, picking up and putting down the object and picking up and shaking a toy. These movements were used in establishing understanding of cause and effect by the child and familiarizing the child with the robot as shown in Fig. 9.

IV. Results

The CRS robot system specifications shown in Table III far exceeded the requirements for this application. The robot was typically operated at a speed setting of 20–40% of maximum and the payload for the task utilized was less than 0.25 kg. The reach of 710 mm was extended by approximately 150 mm by the gripper. The Cartesian coordinate calculations did not cause a delay in response that was noticeable to the children. Because of the high performance of the robot relative to the application, there were no limitations placed on the application by the technology itself. The major limitations in the system were in the

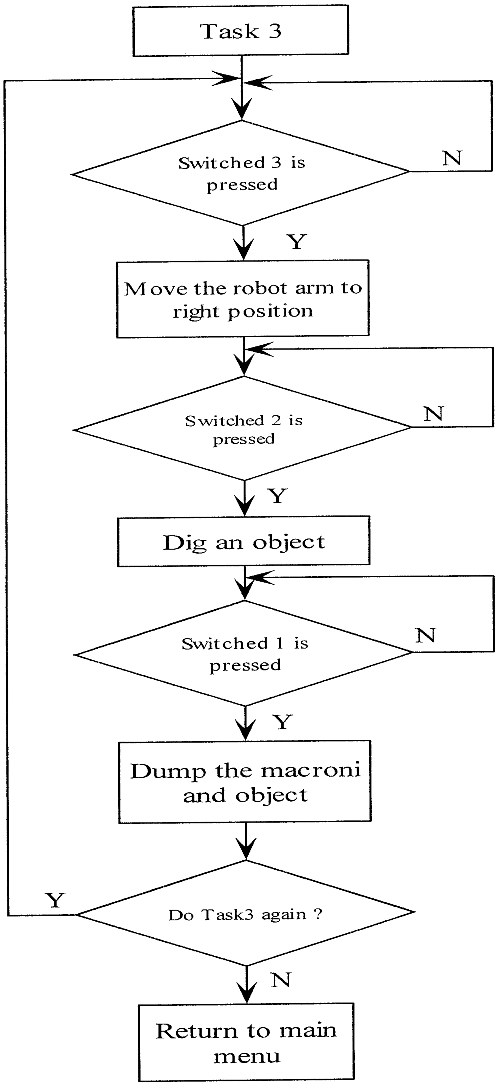

Fig. 8. Software control for switch controlled playback of movements by individual user interface switch.

positioning of the switches for the children to effectively activate them when desired and avoid accidental activation. The majority of the children tested to date have used head control. This has made it difficult to find a switch location that the child can reliably activate. The existence of positioning equipment such as head rests contributed to these difficulties. Many apparently accidental activations were caused by a child hitting one switch with the back of his or her head while attempting to hit another switch with the temple of the opposite side of the head. Scanning has been difficult for the children in our studies to use. These children also had difficulty using scanning in other applications such as computer access or augmentative communication.

The robot system performed well in all of the experiments with no failures of software or hardware. The tasks utilized do not require high precision and they did not tax the robot's capabilities in either speed or accuracy. This allowed investigation of the limitations imposed by the task and the skills of the child, since the robot itself was not limiting in performance. During preprogrammed tasks, the protocol required that the adult place the object to be dug up in a predetermined location. On some occasions the object was not positioned properly and the robot did not pick it up. All children were positioned outside the reach of the robot arm to ensure that they did not inadvertently come in contact with the arm.

Fig. 9. The robot arm provides a means for the child to engage in a play activity by digging up an object and handing it to her adult play partner.

TABLE III
SPECIFICATIONS OF THE CRS ROBOTIC ARM SYSTEM

Performance Specifications		
Payload	2 kg (4.4 lb) nominal	
Reach	710 mm (28.0 in.) without gripper	
Repeatability	±0.05 mm (0.002 in.)	
Work Range and Speed		
Axis	Range	Max. Speed
J1 (waist)	±175°	180°/s
J2 (shoulder)	±90°	180°/s
J3 (elbow)	±110°	180°/s
J4 (wrist rotate)	±180°	171°/s
J5 (wrist pitch)	±105°	173°/s
J6 (tool roll)	±180°	171°/s

V. DISCUSSION

Four children with severe cerebral palsy, aged 6 and 7, participated in the pilot study [4]. All of the children had very limited ability to control their limbs and none were able to speak. All four children had experience using single switches to operate battery-powered toys and to access simple games on the computer. Each child used left and right head rotation to activate the switches for the first two movements (Task 1 and 2 shown earlier). For Task 3, the third switch was activated by the hand for two of the children, behind the left elbow for one and by the right foot for one. None of these children could participate independently in the type of play tasks used in our study. In general, the children had varying degrees of success in understanding and replaying the stored tasks. The amount of prompting and the number of trials required to achieve understanding varied among the children. None of the children showed any apprehension toward the robot. All children understood the one and two switch tasks after a few trials. Understanding of the three-step Task 3 was more difficult, although all of the children appeared to eventually understand it. In general those with lower levels of cognitive function experienced greater difficulty in these tasks regardless of the degree of physical disability. This result is consistent with the findings of Kwee and Quaedackers [14].

A major difficulty faced in all experiments was the mounting of switches for easy, reliable access by the children. Most children had two sites (head rotation) available and they controlled these with relatively ease. Reliable third switch sites were more difficult to determine, but one was found for each child. None of the children had more than three controllable anatomic sites for switch use. In order to uses direct selection, more sites will need to be found and switch mounting will require refinement in future experiments. In the absence of this, scanning will be required and this will place additional cognitive demands on the children.

Inaccurate positioning of objects to be dug up may have caused some confusion in the children, especially during the familiarization period. This will need to be addressed to avoid confusion in future experiments. As the children became familiar with the task and the robot's performance, they appeared to view these robot "mistakes" as amusing, often laughing out loud.

The system as designed has several features that were not evaluated in the pilot study. One option is the capability to allow all switches to be active at all times or to only allow the "correct" switch in a sequence to be active. Only the latter was used in the pilot. Two and 3-D Cartesian movements are available, but were not evaluated because of the physical limitations of the children. The system also allows expanded keyboards to be used for selection. Once again, physical disabilities in our pilot group prevented the use of this option. All of these options will be evaluated in future studies.

In comparison to single function toys and EADLs the robotic system provides significantly more flexibility and versatility. For example, up to 14 different functional reciprocal movements of 6 DOFs and gripper) can be controlled with single switch or keys. This is an order of complexity that cannot be approached in control of 3-D objects with toys or EADLs. The robot allows the child to pause at any time and problem-solve before the next movement. Computer graphics and educational software can allow multiple inputs (especially through keyboards), but they lack the capability for manipulation of real 3-D objects. Using a robotic arm, a child can explore his or her environment reaching for objects, turning them, stacking them, or engaging in more complex tasks. For example, Forman compared the use of a robot and the use of computer graphics for development of skills in causality, coordination of multiple variables, reflectivity, binary logic, and spatial relations using groups of nondisabled children from 3 to 7 years old [16]. He used the robot to investigate the coordination of multiple variables by requiring a robotic arm movement in which the arm held a glass of water and the wrist angle had to be continually changed as the elbow was flexed in order to prevent water from spilling out of the glass. Young children carried out this task as two sequential events rather than a coordinated activity. Older children were able to develop a control scheme that used coordination of the wrist and elbow. This type of task would be very different if presented in two dimensions on a computer screen. For our current work, the robotic system is intended to be a research instrument, not a tool for functional task completion. Cost is not the issue at this time. Rather, our goals is understanding of the benefits and limitations of robotic technology for development of cognitive and language skills.

VI. Conclusion and Future Directions

The robot manipulator described here has been developed to allow children who have severe disabilities to explore their environment and engage in manipulative play. The overall objective of our work is to evaluate the impact on cognitive and linguistic function of such manipulative exploration and play. The population of children for whom the robotic system is targeted has severe and multiple disabilities. This creates a need for flexibility in the design of the user interface and the control software to allow for a wide range of cognitive and physical skills in the children participating in our studies. In our pilot study we learned that the physical limitations of this population of children required very simple control interface that could be controlled by gross body movement. In order to achieve higher levels of functionality in the robot (i.e, beyond prestored movements) we will either need to find additional control sites or rely on indirect selection techniques such as scanning. The latter approach increases the cognitive demands on the child. We are exploring all of these options in our current studies. For example, we are exploring the two dimensional positioning of the arm by the child using head movements. This additional capability will allow the child to explore by moving the robotic arm over the tub and then digging in the macaroni to find hidden objects. This generalization of the "move" aspect of Task 3, will facilitate the evaluation of exploration and discovery by the child. We are also exploring general 3-D movements using the features of the user interface described in Section III.

We also learned that familiarization and practice improved performance and lead to greater understanding of the tasks by the children. For this reason, we are studying the use of a robotic system in a school context, in which a robotic system is located in a child's school for a period of 4 wk [17]. This paper includes children with a wide range of physical and cognitive skills and it will allow us to further define both the physical and cognitive characteristics required of the user interface. This is in contrast to the study reported here, in which the child interacted with the robotic system in a few sessions in our clinical setting.

Additional future studies include play interactions between children and other activities that require turn taking and interaction by the child and his or her play partner. Our longer-term goal is to more directly study the interaction between cognitive and language development an the use of the robotic arm. Dunham *et al.* investigated the use of a robot to develop verbal discourse and social interaction [18]. These investigators studied the language used by 2-yr-old children and how this use was altered by interaction with two types of robots: one which spoke to the child (termed "reciprocating") and one which did not. The child was able to control the robot's movements in both cases. Dunham found those children's use of language increased when the reciprocating robot was used and was greater than with either the nonreciprocating robot or toy use. Similar results were obtained using a robot to teach preschool children about birds [19]. The children responded most strongly to a robot that not only spoke, but also had human-like features. Animation, speech, and realistic movements all had a positive effect on the children's learning. These studies were conducted with simple and inflexible robots and the subjects were all nondisabled children. One example of the use of a robot to evaluate social discourse investigated three play conditions: 1) computer graphics; 2) a robot; and 3) deactivated toys (i.e., children played without electronic computer or toy) [18]. The subjects included four nondisabled children matched in age and gender and four children with disabilities. The ages were from 4–7 to 5–2. Dyads of nondisabled and disabled children were formed for the experiment. The data collected were the percentage of intervals each subject engaged in socially directed behavior. Socially directed behavior was recorded if any of the following occurred: 1) one child emitted a vocalization; 2) one child addressed the other by name; 3) there was physical contact between the children; and 4) the children cooperatively used the computer or robot. The use of technology resulted in higher percentages of socially directed behaviors in all children compared to playing only with each other. The computer generally resulted in higher percentages than the robot. The robotic system described here is well suited for studies such as these with children who have severe disabilities.

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