Using a Robotic Arm System to Facilitate Learning in Very Young Disabled Children

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***Abstract*—A robotic arm has been developed to provide a learning environment for very young disabled children. The system allows development of manipulative skills through a flexible and adaptable control system. Arm movements which are of interest to the child may be trained and stored for replay by the child. A flexible set of adapted inputs is provided to accommodate for varying levels of physical and cognitive capabilities in the child. Monitoring and data display functions allow assessment of the child's interaction with the system and the nature of the learning which is taking place.**

Introduction

The normal infant, once believed to be a passive receiver of information, has been found to be a busy, purposeful interactor with the environment [1]. For example, what was once believed to be "just play" has come to be recognized as purposeful exploration and interaction with the environment. The primary purpose of play is to develop collateral skills such as physical development, language, fine motor skills, and socialization [2]. The disabled child lacks physical and/or cognitive abilities which severely limit the development of these skills through environmental interaction. The inability to manipulate objects has secondary effects of lost opportunities for learning about these objects and developing important cognitive and language concepts. This lack of interaction with objects is part of an overall dependence termed "learned helplessness" which results when children feel they have no control over situations [3].

The microcomputer has been used to aid in the development of interaction skills in two ways [4]: as a contingency controlling system and as a monitor of the child's performance. As a contingency controlling system, the computer can alter the prerequisites for environmental interactions by allowing simple gross body movements to serve as controlling actions, and the computer can provide a wide variety of environmental effects when the child does perform a purposeful movement. The second role for the microcomputer is as a monitoring system to assess the degree of interaction and learning which is taking place. This monitoring of the child's performance is crucial to our perception of progress toward learning goals which we establish.

Brinker and Lewis [5] used the concept of cooccurrences, the provision of a contingent result when the child carriers out a purposeful action, to foster the development of interaction skills. They implemented this approach using a microcomputer to provide both contingency control and monitoring [6]. Contingent results used by Brinker and Lewis included graphics, toys, and tape recordings of songs or voices. Brinker and Lewis collected data on the number of switch activations and observable behaviors of the infant. The computer was also programmed to modify contingencies based on the frequency of switch activations. Data reflecting the number of switch hits as a function of time for various contingencies were displayed at the end of each session. This display was used to show parents how the child was interacting with the system. This work showed that children as young as three months would develop purposeful movements to cause the contingent result. Behrmann and Lahm [7] used similar contingencies, and they also collected data representative of the degree of interaction which the child had with the system. The success of Brinker and Lewis and Behrmann and Lahm in using computers with very young children has led to the widespread integration of computer-assisted intervention into early childhood programs.

During the first two years of life, the child interacts with the environment primarily through actions on objects, with social interaction being closely coupled to object interaction [8]. As the child develops, the schemes used for relating to objects change. Prior to four months, the child uses "primary circular reactions" such as mouthing and holding to interact with objects. The 4–8 month old child develops "secondary circular reactions" such as hitting or patting an object, hitting two objects together, shaking, pushing, or waving objects. He or she also examines objects in an exploratory manner. At this level, the child also begins to use differentiated schemes. The child selectively adapts actions to accommodate for the properties of the object (e.g., sliding the object on a surface, tearing the object, and putting one object into another). In the 8–12 months range, the child begins to coordinate the secondary schemata by dropping objects intentionally and displaying socially instigated be-

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TABLE I
ROBOTIC SYSTEM INTERACTION RELATED TO DEVELOPMENTAL LEVELS

Level	Developmental Age	Stage	Typical Actions (mo.) (from 9)	Use of Robotic Systems	Example Robotic System Tasks
I	5 - 7 mo.	3	reinitiates familiar game during pause (5) finds object hidden behind or under a screen (6) transfers object hand-to-hand (6-8) leans forward to search for a dropped object (7) imitates novel body movement (6)	use only as an interesting "toy"	1. interesting which are "played back" with one switch press
II	8 - 10 mo.	3-4	anticipates circular trajectory of object (8-10) drops one object to reach for another (8) moves to obtain object out of reach (8-9) pulls support to obtain object without demo (8-10) uses one object as a container for another (9)	use robotic system to replay a movement and obtain or find object	1. retrieve object located on table with continuous switch activation 2. obtain object by tipping cup, continuous switch use 3. find object behind a screen (table), continuous switch press
III	12 - 15 mo.	4-5	pulls string to obtain object without demo (12) retrieves object by pouring if container too small for hand (12-14) hands mechanical toy to person to be started (12-15) uses string to obtain object against gravity (13-15) moves around barrier to obtain object (15)	use component movements to complete an entire task	1. use two switches to obtain an object via component movements, continuous switch press required 2. same as #1, but find an object hidden from view
IV	15 - 22 mo.	5-6	uses tool as extension of body to obtain object (15-18) finds object where last seen or usually kept (15-18) opens box to obtain object without demo or seeing object placed in box, no trial/error (15-19) imitates 2-action combinations (18-20) anticipates result of actions and adjusts behavior accordingly to situations and problems (19-20) attempts to activate mechanical toy without demo (21) can anticipate means/end and result of applied means (22)	move from component movements to independent control in 3 dimensions	1. use three switches to complete a movement with 3 parts 2. two dimensional (x,y) control with two switches, object on table 3. three dimensional movement

havior such as pretending to drink from a cup, driving a toy car, etc. The child also begins to show objects to others. "Tertiary circular reactions" occur in the 12–18 month age range. Here the child begins to stack and knock over blocks, insert objects into containers and then dump them, etc. Functional uses of objects are also evident (e.g., eating from a spoon, brushing hair, and kissing a baby). The child in this age range also gives an object to another person suggesting social interaction. In the 18–24 month period, the child invents new means to accomplish ends through mental combinations. This child will spontaneously name objects, use one object to stand for another in games and group collections of objects. Table I lists typical actions of infants in the first two years of life.

This paper describes an alternative approach which provides a generalized manipulative capability for disabled children and which builds on the earlier work with microcomputers and very young children. Our system utilizes a small robotic arm integrated into a flexible control system to provide general purpose manipulation of objects by developmentally delayed children. We have developed an integrated approach to the use of technology which provides a logical progression from the simplest form of object interaction to the symbolic representation required for the development of language skills.

EXPERIMENTAL SYSTEM

Our major objective is to create a learning environment for young disabled children which mimics the world of the able-bodied child as closely as possible. Since we want to involve the child in this environment at a very young age, manipulation of objects is essential and robotic systems play a key role.

Fig. 1 is a block diagram of our system. The system is based on the MiniMover-5 robotic arm (Microbot, Inc.) and the Apple IIe microcomputer. These components were chosen because of the widespread availability of the Apple IIe in special education settings and the relatively low cost of the MiniMover-5. The arm consists of five main structures: a stationary base, a body, an upper arm, a forearm, and a two-fingered gripper. This arm is anthropomorphic in its structure (1/2 adult human scale), and it can rotate at its base, extend and flex at both its shoulder and elbow, pitch and roll at the wrist, and open and close at its gripper (hand).

We have added closed-loop control to the MiniMover-5 by adding potentiometers to each joint. This was nec-

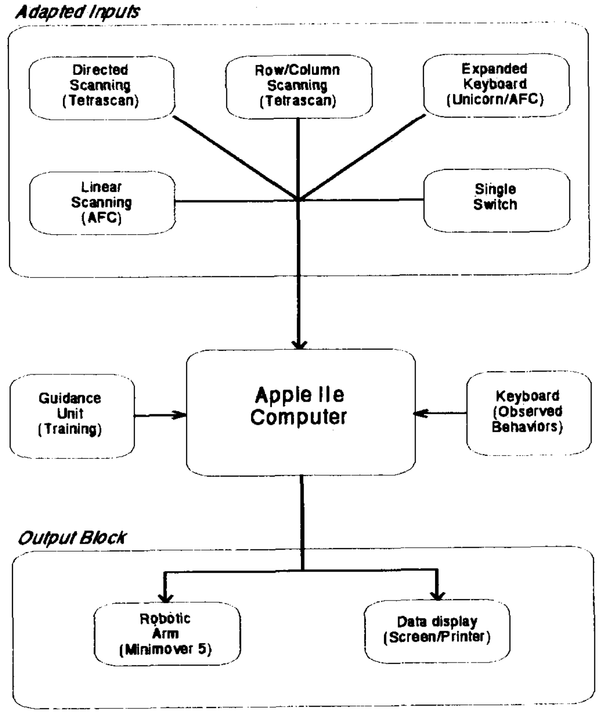

Fig. 1. The robotic arm system consists of a set of adapted inputs, a controlling computer, and the MiniMover-5 robotic arm. See text for a detailed description of all system components.

essary because our preliminary evaluation of the system with young children showed that slippage of the motors and inaccurate manual homing sometimes led to unexpected and confusing results for the child. Closed-loop control avoids this problem, and allows provision of completely repeatable robotic arm movements every time the child activates the system. The closed-loop capability also makes it possible for us to use arbitrary starting points for a movement, and break a movement down into smaller component parts.

Movement Trainer Module

Two ways of teaching the robot to execute a desired movement are included in the system: teaching-by-text (the operator uses textual commands) and teaching-through-guidance (the operator uses a guidance unit to lead the robot along the desired path). In the teaching-by-text mode, one can define actions such as REACH and PICKUP:

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: REACH 200 FORWARD 150 DOWN ;
: PICKUP CLOSE-GRIPPER 100 UP ;
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When REACH is called, either from the keyboard or within a program, the arm will move 2 in forward, and then 1.5 in down. When PICKUP is called, the gripper will close, followed by the raising of the arm for 1 in. Also, a new word REACH-AND-GRAB can be constructed as a combination of previously defined words:

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: REACH-AND-GRAB REACH PICKUP ;
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When REACH-AND-GRAB is called, the entire movement described above will be executed by the arm. The currently available one-dimensional movement directives and their syntax are shown in Table II.

In the teach-through-guidance mode, a therapist uses a joystick (X, Y, Z coordinates) and switches (pitch/roll/gripper open and close) to execute movements (the trajectory through which the arm traces, including both the displacement and orientation of the gripper) which are relevant to an individual child. These movements may then be stored and recalled later in appropriate situations. A movement editor is also included so that a previously taught movement can be modified and given a new name. With this editor, a segment of a movement can be deleted, replaced, appended, or inserted.

The Trainer Module was evaluated by a group of teachers, speech-language pathologists, and therapists. Each evaluator was asked to train the arm to carry out a movement which they thought would be useful in working with very young children, and to edit and play back that movement. A semantic differential [10] analysis was used to obtain the evaluator's opinions of the trainer functions. This group found the system to be easy to use, and they all felt it was capable of producing movements which are meaningful to young children.

Playback Module

The playback module replays a taught movement when activated from the keyboard (for therapist) or from a switch or other adapted input (for the child). At the simplest level, a single switch activation can replay an entire stored movement. Once the child has understood this cause and effect concept, we can progress to multiple switches or expanded keyboards to allow more movements or to break movements down into multiple parts. For the child who lacks the physical control for more than one switch, we can use scanning to sequentially present the additional movements. The selected movement is replayed if the switch is hit when the desired movement is displayed. We can represent the movements with symbols or words and thus help the child develop concepts such as bring, get, etc., These concepts are often difficult to teach without the accompanying manipulation.

As an example of the progression in skill, consider the basic movement of reaching for an object and bringing it to the child. At the most basic level, the system can be trained by the parent, teacher, or therapist to retrieve an object of interest to the child. When the child hits the switch, the entire movement is replayed from beginning to end (one-hit mode). At the next level, the movement will continue only as long as the switch is pressed (continuous mode). This requires that the child understand the need to maintain or repeat switch action. This mode of operation is more "tool-like" and less "toy-like" than the previous stage. Once this concept is established, the arm can be retrained for two movements: 1) move to the object, and 2) grasp and retrieve the object. Two switches labeled with appropriate pictures, words, and numbers

TABLE II
MOVEMENT DIRECTIVES AND SYNTAX

Forth Word	Syntax	
FORWARD	n FORWARD	
BACKWARD	n BACKWARD	
UP	n UP	
DOWN	n DOWN	
LEFT	n LEFT	
RIGHT	n RIGHT	
FLIP-UP	m FLIP-UP	(+P)
FLIP-DOWN	m FLIP-DOWN	(-P)
ROT-CW	m ROT-CW	(+R)
ROT-CCW	m ROT-CCW	(-R)
OPEN	n OPEN	
CLOSE	n OPEN	
CLOSE-GRIPPER	CLOSE-GRIPPER	

n=inchesX100 m=degrees P=pitch R=roll. For example, to move the arm left 2.5 in. n=250, and the correct command is: 250 LEFT.

would be used, one for each movement. The child now needs to learn that the movement cannot be completed by only one action, and that the order in which he does things is important to task completion. After this mode of control is successfully mastered, the child can move on to three movements (e.g., grasp can be broken out of the above sequence and assigned to a third switch). Eventually, the child could have general control over the three dimensions of the arm and open and close of the gripper, and be asked to retrieve the object using only these controls. In this way, the system can allow the child to develop skills and to generalize concepts. Labeling of switches or scanning elements with pictures or symbols portraying the concepts also helps in language development. Examples of robotic movements arranged according to developmental level are shown in Table I.

All switch activations can be set in a one-hit or a continuous mode, each controlled by different software routines. Two types of playback are possible: movements and dimensions. In the movements mode, up to six different previously trained movements can each be assigned to a single switch or scanning element array. When the switch is pressed, that movement is replayed. In the dimensions mode, one switch, expanded keyboard key or scanning array element can be assigned to each of up to 12 of the single dimensions shown in Table II. This allows direct control of one or more of the robotic arm single-dimensional movements. The Unicorn (Unicorn Engineering, Oakland, CA) enlarged keyboard connected to the Adaptive Firmware Card (AFC) [11] may be used for multiple movements or dimensions. In this case, a key size from one inch square to four inches square can be used, and the keys can be labeled with pictures or symbols and/or words.

For the child who cannot use more than one switch, multiple movements or dimensions are accessed using scanning. The AFC allows linear scanning on the bottom of the screen. The movement name or a graphic picture of the movement can be placed on the screen. The scan rate, movement name, movement playback speed, and total number of movements can all be adapted to the individual child. The same options are available for the dimensions option.

Two additional types of scanning are available using the Tetrascan, a keyboard emulator for the Apple IIe [12]. The Tetrascan has an 8 $\times$ 8 matrix of squares each containing an LED indicator. There are six levels associated with each square, three of which are user programmable. Words representing movement or dimension labels can be easily stored for execution of movements. With single switch operation, a row/column scan is used. Using directed scan, a joystick or other set of four switches is used to cause movement of the lighted LED in one of four directions in the array (UP, DOWN, LEFT, RIGHT). The desired square may be selected with either a fifth switch (manual entry) or by pausing for a specified (adjustable) time period (automatic entry).

The playback module was also evaluated by a group of teachers and speech-language pathologists. The semantic differential technique was again applied. Each evaluator was asked to use the system in the expanded keyboard mode to play back three movements which were part of a single larger movement. Then they were asked to use the arm in the dimensions mode. The overall opinion of the evaluators was that the system is usable by professionals working with young children.

Experimental Control and Data Collection Module

Our experimental system also provides for labeling a button or key as corresponding to each of the observable (but not directly detectable) behaviors. The observer presses the appropriate key when a behavior is noted (e.g., directing eye gaze to the object being controlled or to the screen, expressing fear, interest, boredom, etc.). The system also includes a clock, and the program automatically records the time of occurrence along with the coded behavior. At the end of an experimental session, the computer can be used to combine the manually entered behaviors with those directly sensed (e.g., switch activations, robotic arm movement actions controlled) and display the data as a function of time. A hard copy of these data may be obtained using a printer, and the data are stored on disk for later analysis.

Fig. 2 is an example of the data display provided by this system. The horizontal line in the plot represents switch activation for a specific movement or dimension. The vertical axis represents times before (negative numbers) or after (positive numbers) switch activation that an associated behavior was observed and entered. An important aspect of this display is that it allows monitoring of the child's performance in an objective manner. Monitoring of this type is important to assess the degree of learning taking place and the progress toward a specified learning goal.

In analyzing data such as those shown in Fig. 2, the most useful criteria is the time relationship between switch activation and observed behaviors. The individual behaviors are coded with unique symbols, and the degree to which they occur within a specified time window (± 5 s) relative to switch activation indicates how closely the child is associating the switch activation with robotic arm movement. If this association occurs within 5 s before or

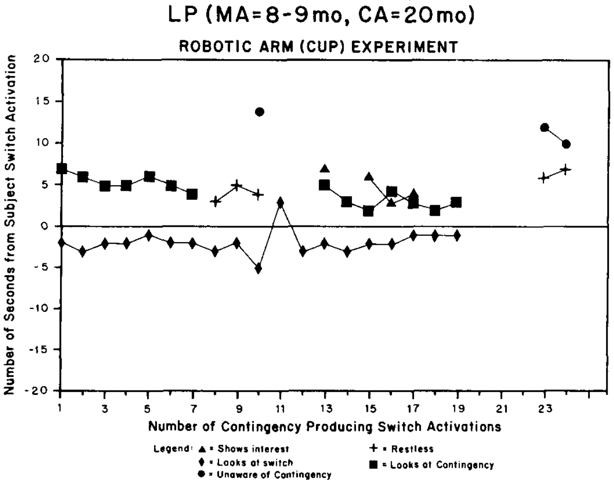

Fig. 2. Sample data display collected during an experimental session with a young child. See text for explanation of the data format and interpretation.

after switch activation, we would say that the child met our "correspondence criterion." If the child met this criterion on subsequent trials, we would conclude that our "repeatability criterion" was also satisfied. For example, in Fig. 2, the child looks at the switch, presses it, and then looks at the robotic arm. This indicates that there is an association between these actions. If there were not this association, then we would conclude that the child was not using the arm as a tool. By collecting data such as that shown in Fig. 2 over a series of sessions, we can note the child's progress and decide when to proceed to more advanced stages. For multiple switches, a trace such as Fig. 2 is obtained for each switch and displayed on the same plot. In this manner, correlations in time between switch activations are determined.

Experimental Use by Young Children

This section describes an example experiment at Level II of Table I. We began with a period of familiarization during which we played with the child and determined what his or her typical responses were to things which they liked, disliked, were fearful of, or bored with. One number key on the computer keyboard was assigned to each of these behaviors, and their occurrences were recorded during subsequent phases of the experiment. We then used either a battery-powered, switch-controlled toy dog or a cassette tape recorder connected to a switch to determine whether cause and effect between the switch and toy movement was understood. We also used this procedure to determine the best switch for the child to use and its location.

Once the child demonstrated cause and effect and we established the best switch and location, we familiarized the child with the robotic arm system. The child was shown that pressing the switch caused the robotic arm to move. We then placed the switch in front of the child and also placed an object to be retrieved by the arm in view of the child but out of reach. The switch was presented to the child and his or her actions were recorded. Data similar to that shown in Fig. 2 were collected and displayed for each experimental situation with each child.

The subjects were six developmentally delayed children with chronological ages less than 36 months and three able-bodied children who were matched in chronological age. All children with an overall developmental age of 7–8 months and greater did meet both the correspondence and repeatability criteria, and those below this developmental level did not. Our subjective observations also supported these conclusions. The children who met the two criteria for interaction with the arm all used it as a tool by pressing the switch only when it was necessary to bring an object closer to them or to uncover a hidden object (e.g., by tipping a cup containing an unknown object).

An interesting result which we observed was that several of the able-bodied children attempted to give the object back to the robotic arm at the completion of a movement. By offering the object to the arm, these children may have been requesting a repeat of the sequence or at least more movement by the arm. This type of interaction is typical of cooperative play, and its absence in the disabled children may be indicative of a more passive and adult-dominated lifestyle.

None of the children in this study appeared to enjoy passively watching the arm complete what we thought would be interesting and novel movements. If the arm was trained to shake a rattle, tip over blocks, or similar actions, the children were generally disinterested after one or two trials, and were satiated quickly. On the other hand, when the arm was trained to bring an object to the child (e.g., a cracker or a cup containing a toy), the children would actively participate for relatively long periods of time (up to one hour in most sessions). This was an unexpected result since we had assumed that novel movements would be of more interest based on our experience with battery-powered, switch-controlled toys. However, this result is very positive in terms of children using a robotic arm system as a manipulative tool to accomplish desired ends. This study demonstrated that robotic system use by very young children is not only feasible, but it is also consistent with our knowledge of development in the first two years of life.

Summary

The system described here has been developed to allow environmental exploration by young disabled children. The combination of adapted inputs, robotic arm training and playback, and experimental control and data collection provide a flexible and systematic approach to early intervention which can facilitate physical, cognitive, and language development in the young child. The inclusion of a robotic arm is central to the goal of enhancing environmental exploration and manipulation. An important secondary benefit of this research is the reduction of dependence which is often concomitant with physical and cognitive impairment.

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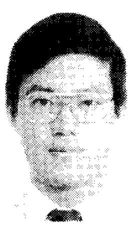

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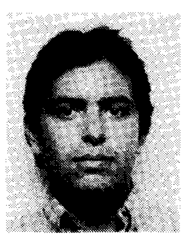
Ronald Y. Lee, photograph and biography not available at the time of publication.



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