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Playing with Toys: Towards Autonomous Robot Manipulation for Therapeutic Play

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Abstract— **When young children play, they often manipulate toys that have been specifically designed to accommodate and stimulate their perceptual-motor skills. Robotic playmates capable of physically manipulating toys have the potential to engage children in therapeutic play and augment the beneficial interactions provided by overtaxed care givers and costly therapists. To date, assistive robots for children have almost exclusively focused on social interactions and teleoperative control. Within this paper we present progress towards the creation of robots that can engage children in manipulative play.**

First, we present results from a survey of popular toys for children under the age of 2 which indicates that these toys share simplified appearance properties and are designed to support a relatively small set of coarse manipulation behaviors. We then present a robotic control system that autonomously manipulates several toys by taking advantage of this consistent structure. Finally, we show results from an integrated robotic system that imitates visually observed toy playing activities and is suggestive of opportunities for robots that play with toys.

I. INTRODUCTION

The role of play in the development of children has been extensively studied, and a large body of work discusses the importance and nature of play in children. Piaget's book "Play, dreams, and imitation in childhood" is one of the earliest references to argue for the importance of play for child development, and the notion that play helps with children's motor skills and spatial abilities [23]. Though the exact nature of potential benefits of play are not fully understood, many believe that it is important for healthy child development [9]. Recent evidence based on studies of play in rats has shown that, at least in rats, play does have an effect on the development of the brain [21] [22] [11].

Controlled scientific studies have shown that early intervention programs for very young children (infancy to 3 years old) can significantly improve cognitive performance over the long term [9] [24]. Due to this evidence, federal and state programs such as IDEA and Babies Can't Wait have been created to identify children at risk of developmental delays, and intervene with therapies designed to promote cognitive development. A common form of intervention is the distribution of toys with the goal of creating stimulating environments for mental development. Although the presence of toys in a childs environment increases the chances of therapeutic play, there is no guarantee that a child will interact with the toys in a beneficial manner with the necessary intensity and duration, especially since children with developmental delays may lack typical interests or get easily discouraged.

Robotic playmates capable of physically manipulating toys have the potential to engage children in therapeutic play, and encourage them to interact with toys in a beneficial manner with sufficient intensity and duration. In this way, a robotic playmate could augment the beneficial interactions provided by overtaxed care givers and costly therapists. As a first step to this type of therapeutic application, we present a robot capable of autonomously manipulating several types of toys. Such a robot could serve as a platform for new forms of educational interaction.

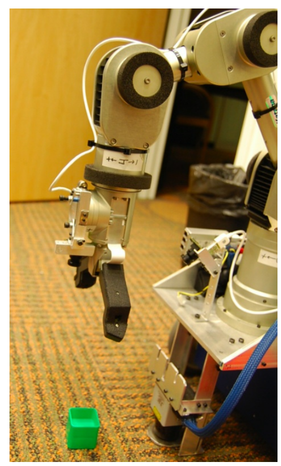

Fig. 1. The experimental platform, including Neuronics Katana 6M180 with an eye-in-hand camera. The other sensors shown are not used in this research.

II. RELATED WORK

There has been significant related work on robots for use in therapeutic play with children. Most of this work has been focused on two areas: robots that are meant to be played with as toys, or robots that assist physically disabled children with play-related manipulation tasks. Some of the key work in this area is summarized here.

A. Robots to Assist Children in Play

Several robots capable of assisting physically disabled children with play-related manipulation tasks have been

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developed. In [14], a teleoperable robot called PlayROB was developed to allow children with physical disabilities to play with LEGO bricks. The robot's workspace includes a LEGO brick surface on which to build structures, with a brick supply system at one edge of the play area. Children with physical disabilities could control the robot using various input methods in order to build structures composed of the LEGO bricks.

Topping's "Handy" robot [27], [26] wasn't specifically designed for play, but instead was designed to assist children with cerebral palsy to perform a variety of tasks such as eating and brushing teeth. However, the robot's use in art and drawing play in children was also examined, and is summarized in [27]. The goal was to allow the children to develop their spatial awareness skills through use of this robot, and to evaluate whether the children were able to use the system and enjoyed using the system. Cook *et al.* have also studied the use of robot arms for play related tasks [3] [2]. This robot was designed to perform play tasks using a large tube of dried macaroni.

These robots are all designed to assist physically disabled children with play related manipulation tasks. In contrast, we are interested in robots capable of autonomously manipulating toys.

B. Robots as Toys

Robots have also been studied in play related tasks where the robot itself is the toy. Some examples of this are Michaud *et al.*'s Roball [15] [16] [17], Tito [15], and the Robotoy Contest [18] [19]. Interactions between children with developmental delays and these robotic toys were studied.

Scassellati *et al.* have studied interactions between robots and autistic children with the Yale Child Study Center [25]. This work demonstrates the potential of robotic toys combined with passive sensing to help diagnose autism in children. This is a strong motivator for using robotic toys equipped with sensing capabilities.

Additional studies involving interactions between autistic children and robotic toys are described by Dautenhahn *et al.* [5] [4] [7][6] and Kozima *et al.* [12], [13].

Although many of these robots are autonomous, they do not engage children in manipulation based play with non-robotic toys.

III. A Survey of Children's Toys

We are specifically interested in play that requires manipulation. In order to determine what capabilities a robot would need to be able to interact with a diverse set of manipulation-based toys, we performed a survey of currently popular toys for children under the age of 2. Based on this survey we have designed robotic behaviors to implement some of the common play behaviors associated with these toys. We selected this age range for two main reasons. First, we are interested in robotic playmates that can promote child development through early intervention, since young children appear to be particularly vulnerable to the environment. Second, we are interested in toys for which autonomous robot manipulation may be feasible in the near term. Our results suggest that this special subset of common everyday manipulable objects may be much more tractable than the objects typically manipulated by adults. As indicated by popular guides to age appropriate toys [8], the suggested age for toys tends to increase with the complexity of the toy in both perceptual and physical terms. For example, toys such as brightly colored blocks, rattles, and baby puzzles are suggested for infants, while toys with complex patterns that require pushing, pulling, rolling, and lifting are recommended for children old enough to walk.

A. Study of Toys

For our survey of toys, we selected the 20 most purchased toys from Amazon.com recommended for children under the age of 2, and specifically designed for manual manipulation. For this particular study, we chose to leave out toys such as stuffed animals and dolls that appear to focus on social interactions. After collecting images for these 20 toys we developed a list of manipulation behaviors relevant to toys for this age range. We then had three lab members individually describe the perceptual characteristics of each toy and the appropriate manipulation behaviors for the toy. If two or more of the subjects agreed that a particular operation was applicable to a toy, we recorded this toy as requiring the selected operation. As depicted in table I, several common manipulation behaviors were frequently reported as being required.

1) Perceptual Requirements: Relative to many objects encountered in everyday human environments, toys for young children tend to have qualities that can facilitate perception by robots. As other robotics researchers have noted, a common feature among toys for children in the 0-2 year old age range is the use of bright, saturated colors [1]. Morever, we found that many toys include bright, solid colors for each distinct, manipulable part of the toy, such as a different color for each block or each button. This was true of 90% of the toys in our study. Our approach to autonomous toy manpulation takes advantage of this by using a color segmentation approach that segments uniform bright solid colors to find the the distinct manipulable parts of each toy.

2) Manipulation Requirements: Toys can support a wide variety of manipulation behaviors, but we found that some manipulation behaviors are much more common than others. In our study we found that grasping, stacking, inserting, button pushing, spinning and sliding were the most common behaviors. We describe these operations in more detail here, and give examples of toys that use these behaviors.

Many toys afford grasping of various objects or parts of the toy. Grasping entails putting enough pressure on an object or a part of an object to be able to move it around in the world. This is required for several of the other operations discussed here. 85% of the toys in our study afford grasping. Examples of toys that afford grasping are blocks, cups, etc, such as the blocks shown with the shape sorter toy in the upper left of Fig. 2.

Toys such as blocks, cups, and other objects are designed to be stacked upon one another. Depending on the toy, stacking may or may not require that the objects have a specific orientation relative to each other. For example, LEGO blocks fit together only in certain orientations. However, simple wooden blocks may not have specific orientation requirements for stacking. Another example of a stacking toy is shown in the upper right of Fig. 2. 35% of the toys in our study can be stacked.

Toys such as shape sorters afford objects to be inserted into other objects. Shape sorter toys include blocks of various shapes (often differing in color as well), as well as a part with correspondingly shaped holes or slots. An example of such a toy is shown in the upper left of Fig. 2. 60% of the toys in our study afford insertion.

Many toys include buttons that can be pressed to perform various functions. This is especially common in toy musical instruments such as the toy piano shown in the lower left of Fig. 2. Many electronic toys include buttons to trigger light and sound responses or motorized movements. 70% of the toys in our study afford button pressing.

Toys such as the trolley shown in Fig. 2 afford sliding motions. The toy shown has brightly colored shapes that are free to move along wires, constraining them to a set trajectory. The shapes are free to rotate about the wires as well. Both of these motions, as applied to toys, generally require grasping some portion of an object and moving it along a constrained trajectory. In the case of spinning, this generally means grasping part of an object in order to rotate it. One example of this is rotating a toy steering wheel. Sliding can involve translation alone or translation and rotation. Many toys also include doors or compartments that can be opened and closed by moving along a constrained trajectory as well. 35% of toys in our study afford sliding, while 25% afford spinning.

TABLE I

TOY MANIPULATION AND PERCEPTION REQUIREMENTS

Toy Property	Percentage of Toys
Bright, Solid Colors	90%
Affords Grasping	85%
Affords Stacking	35%
Affords Inserting	60%
Affords Button Pressing	70%
Affords Sliding	35%
Affords Spinning	25%

IV. AUTONOMOUS ROBOTIC MANIPULATION OF TOYS

Based on the results of our survey, we have developed a robotic perception system and a set of manipulation behaviors specialized for the autonomous manipulation of children's toys. We have validated this system with a real robot using several unmodified toys.

A. The Robot

The robot consists of a Neuronics Katana 6M180 manipulator equipped with an eye-in-hand camera. The arm is attached to a mobile robot equipped with several other sensors and actuators, but for this research the arm was kept stationary, and no sensors other than the eye-in-hand camera were used. This is a 5 degree of freedom arm with a 1 degree of freedom two fingered gripper. The platform is shown in Fig. 1.

Fig. 2. Examples of toys that require grasping, insertion, button pressing, and sliding.

B. Color Segmentation

All vision is performed using the eye-in-hand camera attached to the robot's manipulator. An example image is shown in Fig. 5(a). The vision system is based on color segmentation in order to take advantage of the tendency for toys to have manipulable parts with distinct, solid, high-saturation colors. Furthermore, many toys appear to share similar, commonly occurring colors, so we trained the color segmentation system to classify pixels into these commonly occuring color classes using Hue-Saturation color histogram models. After classification, connected components and morphological operators (erosion and dilation) are used to segment the classified colors into significant regions of colors. This relatively simple, well understood vision system is well suited to the domain of children's toys.

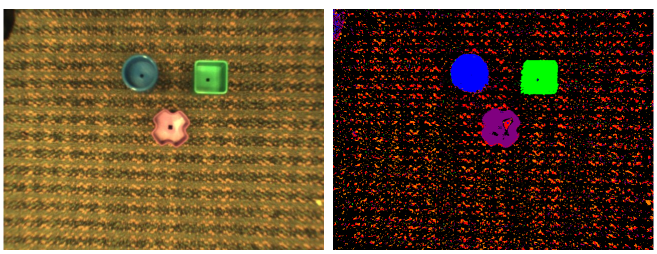
In more detail, each image is taken with the eye-in-hand camera and converted into the Hue, Saturation, Value (HSV) color space. Hue and saturation describe the color, while the value describes the brightness. In order to reduce the effect of lighting conditions on the color segmentation, only the hue and saturation are used to segment the colors in the image. A two dimensional histogram (H by S) is built for each color class. These histograms are constructed as follows. A set of seven desired color classes are selected: red, green, blue, orange, yellow, purple, and black. For convenience, a name and representative color (R,G,B) is selected for each color class, such as "red" or " blue". A set of images of colored objects are taken. Corresponding labelled images are created by labeling each pixel of each camera image with the color of its desired color class. Examples of camera images are shown in Fig. 3, and the corresponding labeled images are shown in Fig. 4.

After the set of raw and labelled images have been generated, the histograms are built. Although any size of histogram is supported, the work described here uses 32x32 histograms. These histograms are used to determine which color class each pixel of a new image belongs to. For each pixel of a camera image, the value of the corresponding bin in each color histogram's color class is selected. The pixel is assigned the color class of the maximum likelihood histogram. An image after assigning colors to each pixel is shown in Fig. 5(b).

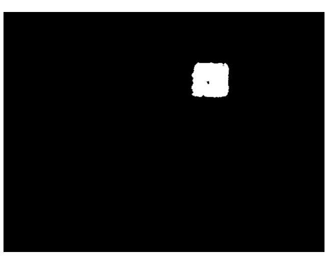
After classifying the pixels into the color classes, we find connected components using four connectivity. The resulting color regions are then cleaned up using erosion and dilation (morphological operators) to reduce the effect of noise or small color blobs that are not part of objects. An example of an image processed in this way is shown in Fig. 5(c).

Fig. 3. Camera images used in generating color histograms

Fig. 4. Labeled images used in generating color histograms



(a) Camera images used in generating color histograms (b) Labeled images used in generating color histograms



(c) Example image of some blocks as seen from the eye-in-hand camera

Fig. 5. Color Segmentation

C. Grasping Controller

All of the manipulation behaviors make use of a grasp controller that performs overhead grasps. The grasp controller initially takes an (x, y) position and an orientation θ as input, which causes the gripper to be placed over the position (x, y) on the plane in front of the robot, and rotates the gripper by θ around an axis of rotation that is parallel to gravity and orthogonal to the plane. The grasp controller can then be commanded to descend and grasp an object below it using tactile sensing performed by IR range sensors and force sensitive resistors (FSRs) in the fingers. This tactile sensing is used to determine when to stop descending and start closing the gripper, and how much to close the gripper. One of the advantages of this grasp controller is that it positions the eye-in hand camera such that its optical axis is normal to the surface the robot is manipulating on. This allows us to form an image where the extent of the objects, excluding height, can be seen from above. This also positions the Infrared distance sensors in the hand over the plane so that the height of an object under the hand can be estimated.

D. Toy Manipulation Operations

We have implemented several of the common behaviors identified through the survey of children's toys. Each of these behaviors makes use of the color-based perception system and the overhead grasp controller, using the robotic platform described above. Because a color segmentation approach is used, only toys where each part is a solid color distinct from its surroundings are suitable. Also, the arm used for this research has 5 degrees of freedom, which constrains its ability to reach arbitrary locations with arbitrary orientations. The grasping controller described above allows for interactions with toys that can be manipulated using overhead manipulation strategies, which rules out toys that require manipulations on the side of the toy.

1) Grasping: The grasping controller for the arm as described above is suitable for grasping some toys where an overhead grasp is suitable, such as many blocks. For this work, we assume that we can segment objects from their environment and from other objects based on their color. This works well for objects such as colored blocks. A grasping controller using this type of perception was developed, and is described here. This controller will locate a block of a particular specified color and grasp it using the manipulator. In the case of multiple regions of the specified color appear, the largest region takes precedence.

First, the robot scans its environment by moving its arm (with eye-in-hand camera) above several points in its workspace, allowing it to see the entire workspace. An image is taken at each location, and color segmented using the technique described above. Once a color region of the specified color that is an appropriate size has been identified, the gripper is positioned above the centroid of this color region. The arm then moves down towards the plane until the Infrared distance sensor in the palm reports that the nearest object is closer than a specified threshold. The gripper then closes on the object until the pressure sensors in the hand report that the pressure being applied is above a specified threshold. The arm then lifts the object up by moving away from the plane. The grasping behavior is shown in Fig. 6(a).

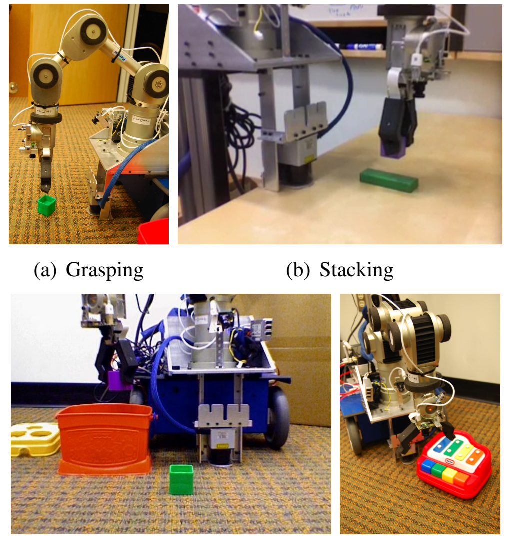
2) Stacking: A stacking controller was also implemented, which allows an object to be stacked on top of another object. In contrast to grasping, stacking requires interaction with two different objects. Here the color of both objects must be specified: for example, specifying 'blue' and 'green' would attempt to stack the blue block on top of the green block. Because the view of the eye-in hand camera is partially occluded when an object is being held by the manipulator, both objects involved in the stacking operation are perceived prior to grasping. This is done similarly to the grasping controller by moving above the two regions in order to determine their positions, followed by grasping the object that is meant to be placed on top of the other object. After the grasp is complete, the arm positions itself above the bottom object using the position saved prior to grasping. Finally, the arm lowers itself to a specified height, and releases the top object, creating a stack. The stacking behavior is shown in Fig. 6(b).

3) Insertion: An insertion controller was also developed, allowing objects to be inserted into holes in other objects. Similar to the stacking controller, the arm first moves over the object to be inserted and remembers this location. The arm then locates color regions corresponding to the hole that the object is to be inserted into. Once the correct location has been identified, the object to be inserted is grasped, positioned above the hole for insertion, lowered to a specified height, and released.

4) Button Pressing: The button pressing behavior is similar to the grasping behavior in that it involves positioning the gripper above a color region. However, instead of descending until the distance sensor in the palm is triggered, a height to press down to is specified to the controller. Making contact with a button is not sufficient to actually press it; to achieve its function it must generally be pressed down some distance. Because this distance varies, the button pressing controller that has been implemented currently requires the desired height to be specified. A force controlled arm would be better suited to this type of operation, but the arm used supports only position control. The controller will position the arm above the color region of the desired color, and then move down to the specified height with the gripper closed (with the fingers touching, instead of spread apart). The footprint of the closed finger is fairly large, so buttons cannot always be pressed accurately. The button pressing behavior is shown in Fig. 6(d).

V. Imitation of Human Play

An effective robotic playmate should interact with the child as well as the toy. As a first step for interactivity we have developed an integrated system that imitates human play, shown in Fig. 8. In this scenario, the human has a toy that is identical to the robot's toy, so that the human and the robot can play side by side. This integrated system combines the previously described autonomous robot manipulation system with an additional perceptual system that interprets human play in terms of high-level behaviors that match the autonomous systems behaviors. This perceptual system operates independently from the robot. It consists of a fixed camera that observes the workspace of the human and a client that communicates with the robotic system's server via sockets using high-level commands. This perceptual system



(a) Grasping (b) Stacking

(c) Insertion (d) Button Pressing

Fig. 6. Toy Manipulation Behaviors

Fig. 7. The toys that the system has successfully played with in informal testing.

makes use of the same common appearance characteristics of toys in order to interpret human play. Play interactions with a human are demonstrated, but interactive play between children and the robot is future work.

A key aspect to the success of this integration is the use of high-level manipulation behaviors for communication. This enables the integrated system to avoid issues with transforming the two system's distinct perspectives. For example, the human is observed from a fixed camera with a side view, while the manipulation system observes the toys with a moving, eye-in-hand camera with an overhead view. Due to the use of high-level operations this discrepancy does not cause any difficulties.

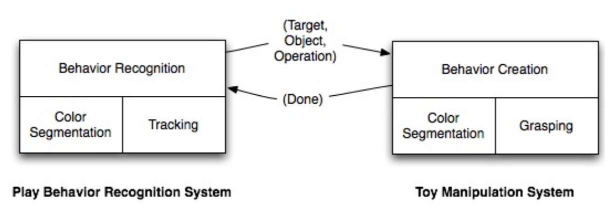


Fig. 8. Block diagram of the system interaction. The systems are highly similar in their structure.

A. Play Behavior Recognition System

In order to recognize play behaviors, this additional perceptual system identifies and labels the sequence of motions associated with a play behavior. Instead of monitoring the movements of the person's body, this perceptual system monitors the movements of the toy. A toy of interest is first identified and then tracked over subsequent motion frames. A set of individual motions is then recognized and used to identify the corresponding play behavior. Previous work with this system was presented in [10]. Activity recognition with respect to play behaviors has also been addressed by other related work, such as [20].

1) Object Detection: In a similar manner to the eye-in-hand perception system, detecting toy objects in the scene consists of three primary steps - RGB to HSV color conversion, histogram back-projection, and segmentation. Since most childrens toys use saturated colors to keep visual attention, we use color as the key feature for detecting an object. During a human playing action, a color input image is captured at 30 frames per second and converted into a one channel Hue image. This image is then back-projected with a pre-defined histogram to segment color. Each segmented group is then re-examined to eliminate outliers and unsymmetrical contours. Through this process, individual toy objects resident within the image are identified. An example of this process is shown in Fig. 9.

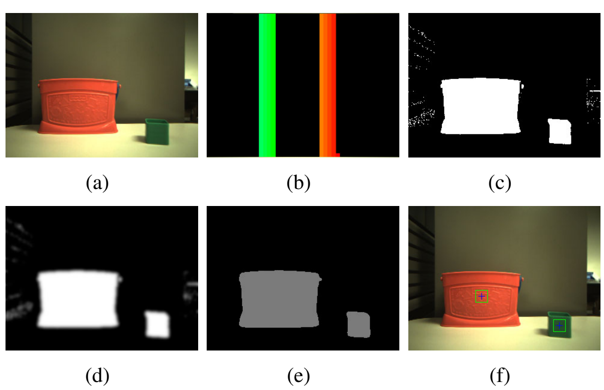


Fig. 9. (a) Original Toy Scene Image (b) Back-projected Hue Histogram (c) Histogram Back-projected Image (d) Smoothed Image with Gaussian Filter (e) Binary Thresholded Image (f) Final Toy Objects Detected

2) Object Tracking: Among the multiple toys detected, the first one to take an action is considered as the play object. The other toys are then marked as targets, and the motion of the reference toy is described relative to them. Object tracking involves the repeated process of object detection, in which the back-projection histogram only references the color of the play object. (Fig. 10)

3) Play Behavior Recognition: Using the motion behavior analysis process, individual behaviors are identified and sequenced based on movement of the play object. The final resting destination of the play object is then used to identify the final play behavior. For testing results, we select two behaviors- 1) Insert: after a downward motion towards the target, the play object disappears, and 2) Stack: after a

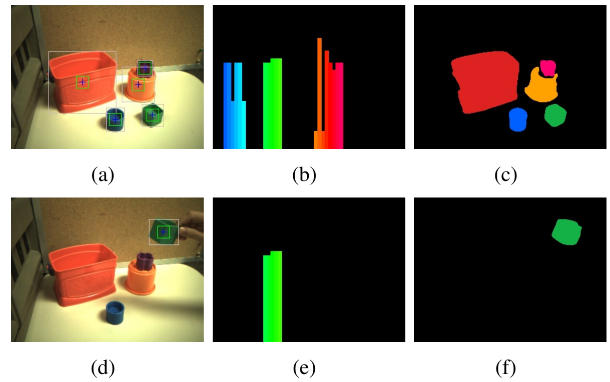


Fig. 10. (a) Toys Detected in Scene (b) Back-projected Hue Histogram (c) Resulting Color Space (d) Play Object Detected in Scene (e) Back-projected Play Object Hue Histogram (f) Resulting Play Object Color Space

downward motion towards the target, the play object is placed on top of the target.

VI. Evaluation of the Integrated System

We performed a test of the integrated system's ability to perform turn based imitation. The play behavior recognition system was used to track a human manipulating some toys. After a toy manipulation operation was performed by the human, a message was sent to the robotic toy manipulation system, which would perform the same task, and notify the human when it had completed the task.

In order to perform these experiments, the play behavior recognition system and the toy-manipulation system used different computers that communicated using a simple message protocol over the campus network. Upon recognizing a manipulation operation, the play behavior recognition system would send a message to the robot using the following format: { TargetColor ObjectColor Operation}. The robot would then carry out the same task on the toys in its workspace. Upon completion of the task, the robotic system would send a simple reply of { Done } to notify the other system that it was ready to perform another manipulation task.

Two types of manipulation operations were tested: stacking, and insertion. The button pressing operation was not tested in this experiment, as it was implemented only on the robot, not in the play behavior recognition system. The same set of toys was placed in the field of view of both systems for each task. The toys were each brightly colored and solid, and each toy in the field of view at a given time had a unique color. The toys used were green, blue, and purple blocks, orange and red cups, and a large red bin.

Two human subjects participated in the experiment, and each completed eight manipulation tasks using these toys. We show the results in Table II. The two failures that occured involved the purple cross-shaped block, which had a tendency to slip out of the robot's simple 2-finger gripper.

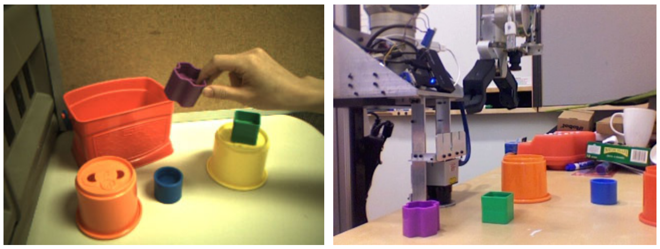
VII. Conclusion

Toys for young children represent an exciting realm for autonomous robot manipulation, where there is the opportu-

TABLE II

RESULTS FROM THE TOY MANIPULATION EXPERIMENT

Operation	Subject 1	Subject 2
Insert Green block into Red bin	Success	Success
Insert Blue block into Red bin	Success	Success
Insert Purple block into Orange cup	Success	Failure
Insert Blue block into Orange cup	Success	Success
Stack Green block on Orange cup	Success	Success
Stack Green block on Red cup	Success	Success
Stack Purple block on Orange cup	Failure	Success
Stack Blue block on Red cup	Success	Success
Total	7/8	7/8



(a) Play Behavior Recognition System (b) Robot Manipulation System

Fig. 11. Experimental Setups

nity to both develop systems that manipulate unaltered, yet relatively simple, human objects and create robotic systems capable of enriching the lives of children. This simplified world of manipulation could serve as a valuable stepping stone to systems capable of manipulating everyday objects beyond toys.

Within this paper, we have demonstrated a system capable of participating in manipulation based play with a human that takes advantage of the structure of children's toys. The system can perceive brightly colored toys, and perform several common manipulation behaviors on multiple, unaltered toys.

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