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Developing and Benchmarking Show & Tell Robotic Puppet for Preschool Education

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***Abstract*— Robots have been shown to assist in education and development of social skills in children. However, there has been no study yet that benchmarks the effectiveness of robots with respect to traditional playtools found inside a classroom, such as pretend play items and blocks. This paper presents the design, development and testing of robotic puppets, which would be used to support teaching in kindergarten education. Different types of robotic puppet design were considered before settling on a glove-type puppet. To benchmark the robot performance, a total of 52 five year-old children were observed, from which quantitative and qualitative data were collected. The result of the study indicates that when playing with the robotic puppets, the performance of the children with respect to thinking and learning, creativity and imagination, and social interaction and independence, is comparable to other traditional playtools.**

I. INTRODUCTION

Play as part of children's learning activity has been shown to contribute positively to a child's physical, social, emotional, and cognitive development [1][2]. In early childhood education, there is a consistent push to include more play in the curriculum. Access to tools or technology, which could assist children in playing, could benefit both structure and unstructured play. Robots is a technology-based playtool that could be incorporated in early childhood education.

Recent years have seen impressive advances of robotics in the field of education and therapy [3]. In [4], Robovie robot was used to encourage learning of Lego Mindstorms, so the robot was designed to be a facilitator. QRIO robot was used to study socialization or bonding between robots and toddlers [5] where it was shown that robots could become part of a social ecology that includes the teacher, the students, and the robot. In their case, QRIO was designed to have various characters which could adapt to the different needs of the students. Bers et al. [6] have studied the use of Lego Mindstorm and ROBOLAB in encouraging students to explore and learn. The key to the successful implementation of robotics in pre-school education in Japan is the use of Keepon robot [7].

A survey of state of the art shows puppets being robotized [8][9]. There are several forms of puppets which are widely and frequently used nowadays, most notably marionette, rod and glove puppet. While marionette was successfully robotized by Chen et al. [8] and a finger puppet by Hu et al. [9] there has been no such attempts to robotise rod or glove puppets. More importantly, the robotized puppets reported in literature were not implemented for preschool education applications nor was there any benchmarking study done on the effectiveness of these robotic puppets.

This paper attempts to address some of the gaps mentioned above. First, the development of a robotic glove puppet, from design to testing will be discussed in the succeeding chapters. Secondly, a benchmarking scoring system adopted from the education field will also be presented and discussed. With this paper, we hope to contribute to the growing body of research on educational robots by presenting a robot for preschool children and an evaluation method of such robot's effectiveness.

II. PUPPET REQUIREMENTS

To evaluate robots for kindergarten education application, we decided to robotize a puppet. Choosing the type of puppet is tricky since there are several types of traditional puppets including glove, sock, finger, rod, marionette and shadow puppets [10]. Aside from the marionette [8] and finger puppets [9], which had been successfully robotized there had been no such attempts for rod and glove puppets. The rest of the discussion in this section focuses on rod, glove and marionette puppets and why glove puppet was chosen to be robotized.

A. Design Requirements

The primary factor to consider is safety since the robots would be used by kindergarten children (4-6 year olds). Using *ISO-8124* (International Standard) and *EN-71* (EU Standard) as basis, the robots to be built should have the following characteristics:

- No detachable/removable small parts to prevent swallowing, choking or aspiration.
- No exposed wire and electrical parts to prevent shock.
- No brittle parts or sharp points or edges that could cut fingers.
- No exposed strings or long cords that could strangle users.

Additionally, the following criteria should also be considered:

- Simplicity - The robot must have simple design and control to enable easy and intuitive use. Simple design also lends to easy maintenance and low production cost.

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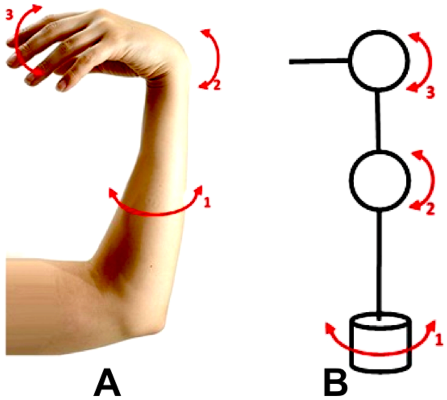

Fig. 1. Mapping of the hand (A) to the puppet's kinematics (B) where (1) is the bodys horizontal rotation, (2) is the head's vertical rotation, and (3) is the mouth motion.

Fig. 2. The robotic puppets for show & tell in preschool.

- Durability - The robot must be able to withstand collision, stress and other unforeseen impacts while being used by children.
- Aesthetic - The robot must be able to capture and hold children's attention and interest.
- Reliability - Highly reliable design and construction means minimal trouble during operation, short down time due to faults and minimum maintenance.

Lastly, primarily due to its use as a puppet in a kindergarten school setting, the robot must also have the following functions:

- Driven by actuators that is controlled via the user's motion.
- Accept user's voice as input and mask it to become the puppet's character voice.
- Record the robot's motion and replay it.
- User-controlled via a handheld controller.

B. Puppet Type Selection

Three types of puppets were considered for this project: marionette, rod, and glove. Their designs were analyzed and weighted based on the requirements stated in Section II-A.

Marionette uses string system which requires large number of actuators. The number of motors and the use of strings already requires a complex design that would be difficult to operate by children; the strings could get entangled or accidentally cut during operation. This complexity would also require frequent maintenance and calibration of strings. Marionettes usually possess interesting and aesthetically pleasing designs, but its actuation mechanism's complexity is a liability in a kindergarten setting.

Rod Puppet is relatively less complicated than marionette but still needs large number of actuators. This type of puppet requires solid rods and exposed mechanism to control the puppet body. This could definitely affect safety, durability and aesthetic value of the robot.

Glove Puppet is the simplest among the three. It requires fewer actuators, which can be fully enclosed within the puppet's body. Other components could also be hidden within the puppet's body. This makes for simple design, high reliability and ease of maintenance. The choice of construction material become the issue for a glove puppet.

To aid in choosing the puppet style, a weighted scoring system was developed. Each puppet style was rated 1-5 (5 being the highest) for simplicity, durability, aesthetic, and reliability. Then the criteria was given a weight, with safety being the priority (40%) while the remaining ones gets 15% weight each.

Each rating was converted to a score based on the weight of the criteria. The scores per puppet style were summed to get the total score, which were then ranked to determine the number one style. The details of the scoring is listed in Table I.

TABLE I
CRITERIA WEIGHTS USED TO EVALUATE THE TYPE OF PUPPET TO BUILD

	Marionette		Rod Puppet		Glove Puppet	
Parameter (weight)	Rating	Score	Rating	Score	Rating	Score
Safety (40%)	2	0.80	3	1.20	5	2.00
Simplicity (15%)	2	0.30	3	0.45	5	0.75
Durability (15%)	3	0.45	4	0.60	5	0.75
Aesthetic (15%)	5	0.75	2	0.30	4	0.45
Reliability (15%)	3	0.45	4	0.60	4	0.60
TOTAL SCORE		2.75		3.15		4.55
RANK	3		2		1	

As shown in the table above, the glove puppet garnered the highest score. Thus, the robot was built took the form of a glove puppet.

III. Robotic Puppet Design

The robotic puppet's design are composed of three parts: hardware (mechanical), electronics and software. The final form of the puppet is shown in Fig. 2. We designed the puppet body, base, and controller but the puppet characters were bought off-the-shelf. To change the puppet character, we just need to take out the outer cover and replace it with a different one.

A. Hardware Design

1) Mechanism: As shown in Fig. 1, the puppet's actuation design was patterned after the forearm motion of the puppeteer, where the forearm is the puppet's body, the wrist is

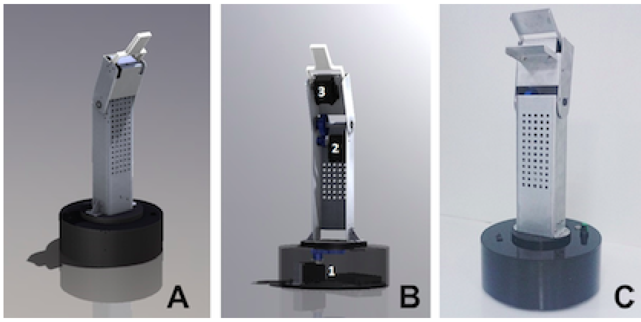

Fig. 3. CAD design of the puppet's body (A); An open view of the CAD design with the motors numbered (B); The actual protoype (C).

Fig. 4. The puppet remote controller.

the puppet's neck and the hand is its head. The arrangement of the puppeteer's fingers naturally form the shape of the puppet's mouth, where the thumb acts as the lower jaw and the other four fingers act as the upper jaw. Based on Fig. 1, the puppet would have three degrees-of-freedom (DOFs) as shown in Fig. 1(B).

The robotic puppet would be able to (1) rotate its body horizontally, (2) rotate its head vertically and (3) open and close its mouth by rotating the upper jaw.

2) Actuators: Given the three degrees of freedom (DOFs) of the puppet, it would have also 3 actuators. The actuators are located within the body of the robot (refer to Fig. 3(B)):

- Motor 1 is located at the bottom of the puppet within the base to drive the entire upper body horizontally.
- Motor 2 is placed within the upper body to act as the puppet's neck and rotate the head vertically.
- Motor 3 is located within the head to open and close the mouth by rotating the upper jaw.

To reduce the high torque caused by the heavy loads of the body and the head, Motors 1 and 2 were meshed with 1:2 gear ratio. Motor 3, which was placed at the top of the puppet, was mounted directly.

The three motors used were Dynamixel AX-12+ servo motors, chosen for their relative ease to program, size compatibility and weight.

3) Dimensions: From the kinematic diagram and motor locations, a CAD drawing was created. As shown in Fig. 3(C), the entire product can be divided into 3 parts: the base, the body and the head.

The base is a cylinder with a diameter of 20 cm and height of 10 cm. It houses Motor 1 and other electrical components of the puppet. The body, connected to the motor in the base via a turn table, has dimensions of 10x5x25 cm. It contains a speaker and Motor 2, which drives the head rotation via spur gears. Finally, the puppet head with 10cm of height, houses the last motor for the mouth motion. In total, the puppet has the dimensions of 20x20x45 cm.

The puppet movement is controlled via a remote control (refer to Fig. 4). In order to meet ergonomic requirements, it was designed to fit comfortably in a child's hand. The remote control was rapid-prototyped using 3D-printing technique.

4) Materials: In accordance with the safety standard for toy design stated in *ISO-8124* and *EN-71*, the upper body is made of 1.5 mm thick aluminium sheet. Aluminum was chosen to ensure that the body can withstand the stress resulting from repetitive motion. On the other hand, the base that houses all the electronic components was made of acrylic to prevent short-circuiting and electrical grounding.

B. Electronics Setup

The electrical setup are divided into 2 parts as shown in Fig. 5 – the remote control and the puppet.

1) Remote Control: The remote control (RC) consists of a micro-controller (Arduino Pro Mini), an Inertial Measurement Unit (IMU), Bluetooth module (BT), a button and a 9V battery. When communication between the remote control and the base is established via Bluetooth, it can transfer the orientation data of the RC to the puppet to drive the actuators. The push button on the RC controls the opening and closing of the puppet mouth.

The main sensor used to detect the motion of the user, which gets translated to motor command of the puppet, is the inertial measurement unit (IMU). It consists of three types of sensors in one packaging: accelerometers, gyroscopes, and magnetometers. A total of nine data is measured – acceleration, angular velocity and orientation in three dimensions. IMU has been successfully used in measuring spatial orientation in infant [11] and children activities [12] and upper arm motion [13][14].

2) Puppet Base: All other electrical components are housed within the puppet base. Similar to the RC, the base consists of a micro-controller (Arduino Mega) for computation and execution, and a Bluetooth module for communication. The motors were driven by the micro-controller through a driver.

The base also consists of an audio module (Arduino Uno + Adafruit Wave Shield), which can receive and process analog voice signal from a microphone, mask the voice signal and output it to the speaker. The parameters for the audio signal masking could be modified via a switch (for the pitch) and potentiometer (for the volume) built into the module.

C. Software

The robotic puppet software does three major processes:

- Establish Bluetooth (BT) communication between the puppet base and the remote control (RC).

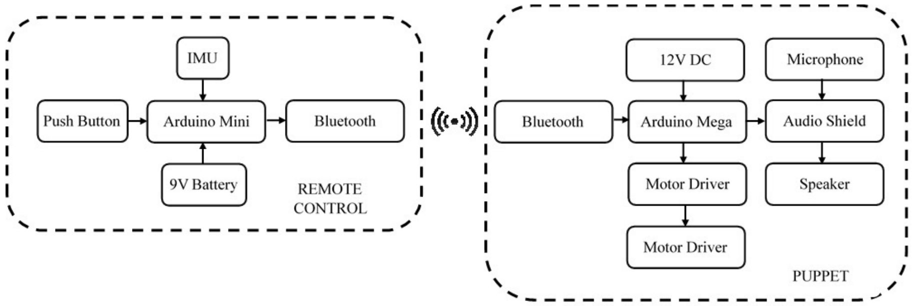

Fig. 5. Block diagram of the electrical setup

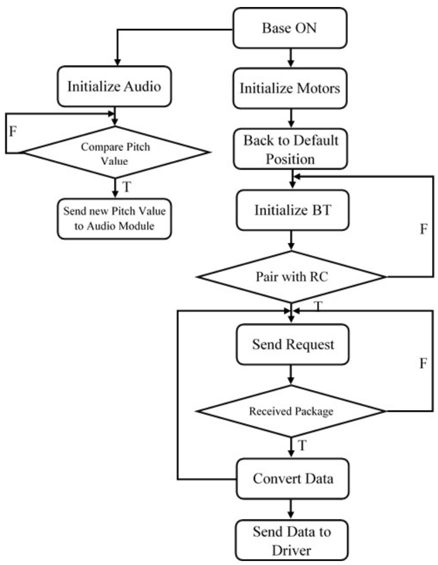

Fig. 6. Flowchart for Base

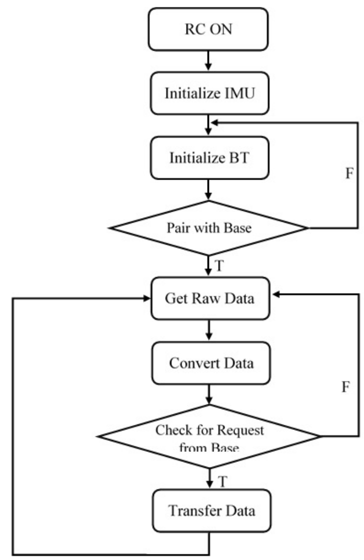

Fig. 7. Flowchart for RC

- Convert the raw sensor data from the IMU into angular data (orientation of RC) and convert it into motor position.
- Accept and process other input from the user such as audio

Fig. 6 and 7 show the flowcharts for the base and the RC. Both systems, when switched on, starts initializing their components.

For the RC, it checks if the IMU and BT are functioning properly and then it would try to establish communication with the base. Once the RC and base are paired, the RC keeps getting and converting raw data while waiting for a data request from the base. The process of converting raw data to angular data was done by using Direction Cosine Matrix (DCM)-based orientation estimation [15][16]. This process will continue until the RC or base is switched off, disconnected or run out of battery. The data package sent to the base consists of angular data of the RC orientation and the binary state of the push button.

Similarly, upon switching on, the base initializes the motors, the audio and the BT modules. In the meantime, the motors return to their predefined default positions. The BT module, after initialized, would try to connect to the RC. Once paired, the base will send request periodically (every 100ms) to get the data package from the RC. The received data then will be convert into motor positions by a mapping function, and pushed to the motor drivers.

During initialisation, the base also checks for the pitch shift value (switch on the audio module), the volume level (potentiometer on the audio module) and feeds these data to the audio module. The audio module receives the analog voice signal and convert it into digital, which is processed by a pitching shifting function and sends the altered voice to the speaker.

D. Safety

Special attention was placed on safety in fabricating the robots. Aluminium and acrylic, the materials used for the body are sturdy, light, and non-conductive of electricity (acrylic). The motors and gears are located inside the robot body and base. The holes on the body and on the joints are either too small for a finger to pass, or covered with puppet's fabric material. For the moving joints, the neck has a built-in mechanical stopper to prevent closing together (and squishing a child's finger). On the other hand, the jaw itself is covered by the puppet's thick fabric material. And like the neck, it has a mechanical stopper to prevent full closure. Lastly, the motor torque applied on the neck and jaw joints are small enough to prevent injury.

IV. Benchmarking Instrument

To benchmark the effectivity of playing with robotic puppet with respect to traditional activities or play tools inside a kindergarten classroom, Toy Effects on Play Instrument (TEPI) scale developed by Trawick-Smith et al. [17], have been adopted. TEPI is a 5-point rating scale used to observe and rate children's play performance across three areas of development: (1) thinking and learning, (2) creativity and imagination, and (3) social interaction and independence. Explanation of the sub-categories under each area of development are found in the list below.

1) Thinking and Learning
    a) Constructing Knowledge - how children show (through behaviors or verbalization) construction of new knowledge (such as new concepts or words) through play
    b) Problem Solving - how children show varied problem-solving skills by considering and evaluating alternative solutions
    c) Inquiry - how children engage in frequent exploratory behaviors by asking questions and taking steps to answer their own questions
    d) Engagement - how children exhibit interest and persist in using it for an extended period
2) Creativity and Imagination
    a) Creative expression - how children use much open-ended, verbal and non-verbal expression; divergent ideas; and some of which are unique and unconventional
    b) Imagination - explore how children create imaginative and complex play narratives
3) Social Interaction and Independent Use
    a) Collaboration - how children show cooperative interactions with their peers; interactions are mainly positive and conflicts are resolved quickly
    b) Independent use - how children play without showing frustration or confusion or making requests for adults' help; they can find meaningful ways to play with the materials

The TEPI scale indicates the performance level or frequency of showing such behaviors. A score of 5 denotes "much expression", 4 means "some expression", 3 denotes "intermittent expression", 2 means "little expression", and 1 means "no signs of expression".

V. Experiment

A. Participants

A sample of 52 children aged 5 to 6 years, recruited from two community-based kindergartens in Singapore, participated in this study. The children came from two different kindergartens, with the first school having 20 participants (9 girls and 11 boys from the same class) and the second school consisted of 32 children (16 girls and 16 boys from three separate classes). Ethics approval was received from the Institutional Review Board and consent was obtained from the two preschools and parents.

B. Observation Process

The schools which participated in this study has scheduled (structured) play for the children at the activity corners, located inside the classroom, for about 30-45 minutes per day. Playtools such as blocks, puzzles, puppets and arts & craft materials are found in different activity corners. The children play at the different activity corners on a rotation basis and they could choose how to play and with whom to play with.

For each activity, each child was observed for approximately 10-15 minutes for scoring (using TEPI) for every playtool. Data gathered was processed using SPSS for analysis.

C. Playtools

Aside from the robotic puppet, two other playtools were chosen for comparison purposes. These are blocks and pretend play. Blocks were chosen since they are very basic and traditional play accessories used by children. Pretend play, on the other hand, refer to items such as fireman's hat or wings, that children could use to do role-playing activities. The contrast between blocks and robotic puppet is wide while it's narrower between pretend play and robotic puppet. Comparing the three playtools side-by-side could provide valuable insight into the true value of using robot in the kindergarten.

The robotic puppets were brought in during the experiment period and added in the classroom as another activity corner.

D. Data Analysis

Repeated measures analysis of variance (repeated measures ANOVA) was used to validate the significance of the mean score differences.

VI. Results and Discussion

A. Inter-rater Reliability

Two raters conducted the evaluation, with the primary rater having a master's degree in early-childhood education. Neither rater had any background or connection with the kindergartens observed. The inter-rater reliability was established by calculating Cohens Kappa statistics. The results indicated good inter-rater reliability with a kappa value of 0.94 (for playing with blocks), 0.94 (for pretend play), and 0.90 (for robotic puppetry). In other words, the observations taken by the scorers were comparable to each other.

B. TEPI Results

The summary of the scoring results using TEPI is listed in Table II.

Pretend play playtool lead the evaluation, scoring the highest on all three development domains. The mean score for pretend play is 3.81 for thinking and learning, 4.57 for

TABLE II

ROBOTIC PUPPET BENCHMARKING USING TEPI [17]

Playtool type	Thinking & Learning	Creativity & Imagination	Social Interaction & Independence
Blocks	Mean: 2.94 (SD: 0.48)	Mean: 3.10 (SD: 0.61)	Mean: 3.23 (SD: 0.50)
Pretend Play	Mean: 3.81 (SD: 0.61)	Mean: 4.57 (SD: 0.57)	Mean: 4.74 (SD: 0.55)
Robotic Puppet	Mean: 3.53 (SD: 0.37)	Mean: 3.81 (SD: 0.60)	Mean: 3.94 (SD: 0.50)

creativity and imagination, and 4.74 for social interaction and independence.

The robotic puppet performed better than the blocks getting 3.53 for thinking and learning versus 2.94 for the blocks, 3.81 for creativity and imagination versus 3.10 for the blocks and finally, 3.94 for social interaction & independence versus 3.23 for the blocks. For the mean calculations, $p<0.001$.

What the data shows so far is that using robotic puppets in kindergarten elicits better performance from the children in terms for the three development domains compared to blocks.

C. Qualitative Feedback from Experimenters, Teachers and Students

During the course of the experiment and data collection, the teachers and kindergarten students have been interviewed for their feedback about the robots. The response had been very positive although some changes were requested by both teachers and students. Children asked for the robots to be mobile so they could move around more conveniently. We have also observed that a slight reduction in the puppet and RC size may be necessary, as some puppets are about half the height of the children.

Children warmed up to the robots immediately, while the general expectation was that the kids would be shy about using the robotic puppets. It also took a shorter time than expected for the children to get familiar with how the robot was controlled. In fact some children were able to troubleshoot issues with the Bluetooth communication between the RC and the base all on their own.

VII. CONCLUSION AND FUTURE WORK

The aim of the paper was to show that robotic puppet could be at least as effective as traditional playtools in affecting developmental domains of children. This paper described the development and quantitative benchmarking of a robotic puppet with respect to other traditional classroom activities and playtools such as blocks and puzzles. Results gathered have shown that robotic puppets are better than other playtools with respect to thinking and learning domains, but not in all playtools. Both the qualitative feedback from the users (children and teachers) and observations of the experimenters provide possible improvements to the current robot design.

Further work is necessary to continue the benchmarking with additional playtools, such as puzzles and arts & crafts, in order for robotic puppets to be considered as fit for deployment in kindergarten classrooms. Moreover, experiments with control groups or pre- and post-test study could also provide further insights into the role of robotics in early childhood education.

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