TofuDraw: A Mixed-Reality Choreography Tool for Authoring Robot Character Performance

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ABSTRACT
TofuDraw combines an expressive semi-autonomous robot character (called Tofu) with a new mixed reality *DigitalPaint* interface whereby children can draw a "program" on the floor that governs the robot character's behavior. Initial evaluations of the *TofuDraw* system with children ages 3-8 suggest that children can successfully use this interface to choreograph the expressive robot's behavior. Our ultimate goal for this tool is to enable young children to engage in STEM learning experiences in new contexts such as creating interactive robot theatre performances.

Categories and Subject Descriptors
H.5.1 [**Multimedia Information Systems**]: Artificial, Augmented and Virtual Realities. Animations. I.2.9 [**Robotics**]: Operator Interfaces.

General Terms
Design, Experimentation, Human Factors.

Keywords
Play, Mixed Reality, Play Spaces, Robotics, HCI, HRI, Tangible Interfaces, Social Robots.

1. INTRODUCTION
To quote Vivian Paley, "*children are story makers and story players*" [1]. To support this in new ways, we present *TofuDraw* as a novel platform that incorporates elements of artistic expression, puppet theater, programmability and controllability into a set of interfaces that allow young children to integrate expressive robotic characters into their story-based play. *TofuDraw* was designed to serve as a link between the physical world and the world children imagine. In this paper we explore using TofuDraw to have children "digitally paint" an executable "program" on the floor that represents the robot's desired behavior or performance (Figure 1). By programming the behavior of the Tofu robot in the physical surround, a connection is sought between the act of "programming" and that of "choreographing" via physical motion. By creating a means of programming that is at its core a form of motion itself, it is hoped that young children do not just use and understand the interface,

but also "become" the interface and "enact" the "program" by engaging in kinesthetic and embodied cognitive processes [2] that respects young children's desire to move through space during play. By doing so, we hope to engage even preschool age children in playful "programming" experiences that foster early forms of computational thinking such as simple versions of sequencing, branching, iteration, and the like.

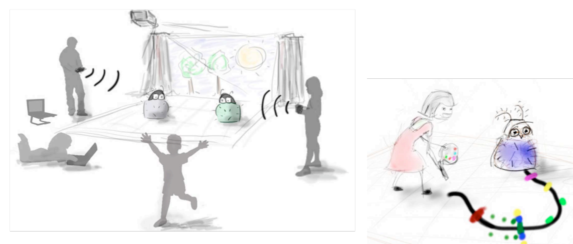

Figure 1: (Left) *TofuDraw*, a mixed reality play space to support imaginative story-based play for young children. (Right) Concept of the *DigitalPaint* choreography interface for authoring the behavior of robot characters in the physical environment.

1.1 Background
Constructionism proposes that people learn more effectively when provided with opportunities to design, create, and build projects that are personally and epistemologically meaningful [3]. *TofuDraw* is built on a constructionist's approach to learning by giving children tools to produce and manipulate personally meaningful artifacts.

The idea of using a drawing to represent choreographed behavior is inspired by *HyperScore* [4], an innovative music drawing program, where the color and shape of the lines represent musical constructs. The resulting drawing is in fact a musical score from which the program executes to generate music. Analogously, users can "digitally paint" choreography on the floor where colored traces represent the movement and expression of the character. The robot "executes" this "choreography painting" as it follows the colored traces.

The idea of drawing the program in the physical surround rather than on a screen is inspired by Ambient Programming and others [5-9]. For instance, in [5] the trajectory of a robotic vehicle is programmed by placing paper cards with special markers on the floor in front of the robot where each mark maps to a behavior that the car performs as it drives over each card. In [6] color is used to denote a program – a crayon drawing, a colorful shirt, anything with color in the world. This allows commands to be more continuous and new programming paradigms are possible where commands are "mixable and smearable".

TofuDraw is inspired by these two prior works where color represents different behaviors. The digital aspect of the "paint" means that the act of programming is not limited by a fixed set of cards, however, and it also supports the flexibility to immediately modify the program through copy, paste and delete sorts of desktop computing functions (that would take more effort if the "program" were drawn on actual paper). Further, the floor-size activity encourages children to move through space and make large brush stroke-like gestures that supports bodily kinesthetic learning [2]. This makes programming a physically active performance that may facilitate a very young child's physical intuition about the representation of the behavior that he/she is creating.

Finally, robots have been used as part of a mixed physical and digital authoring environment for children where stories can be augmented by robots that are controlled by children [9]. In this same spirit, *TofuDraw* strives to bridge these ideas of pretense, story and role-playing with that of transitional object and theatre as microworlds [10].

2. THE TOFUDRAW PLATFORM

TofuDraw consists of a mobile robotic character, a mixed-reality play space, and tangible interfaces that allow children to choreograph the path and expressive behavior of the robot. Through the use of the *DigitalPaint* interface we wish to create a digital medium that can be used to choreograph the movement (path) and gesture (pose and expression) of robotic characters. The "choreography painting" is an abstract representation of the robot's actual behavior, that can then be edited, further elaborated upon, or even erased to start afresh.

2.1 Tofu: The Robot Character

The robot, *Tofu*, is designed to be a "mechanical cartoon" (roughly 12 inches tall) that combines mechanical simplicity with rich expression (see Figure 2) [11]. The most important innovation made with the Tofu robot is the method used for "squash and stretch" -- an important principle of classic animation to bring characters to life [12].

Figure 2: Tofu incorporates principles of classic animation for its expressive abilities.

Three servomotors in the base are configured as winches to provide reasonably fast "squash and stretch" movements as well as different leaning postures. A motor in the head enables the robot to "look around" and do simple by rapid head shake gestures. A pair of small OLED displays mounted on the face are used to animate the eyes. Feathers are the main cosmetic element that adds a plushy softness as well as dynamic secondary movement. The internal foam also makes it squeezable and soft to touch that has a lot of appeal to children. Finally, Tofu can ride on a separate mobile base to navigate through its environment. A small laptop rests on the base and is used to control Tofu and the base.

2.2 Robot Choreography Tools

Like real painting, the child uses a digital paintbrush and palette as the interface to "paint" real-world surfaces with colored light. The digital paintbrush is attached to a palette with a set of colored buttons that allows the child to select the color. There is also an erase button, depicted by a black circle with a white line through it, enabling an erase mode. The digital paintbrush has IR markers mounted on it that are used to track its position and orientation (using a Phase Space 3D motion capture system). Overhead projection is used create a specific color trace of light. By tracking the digital paintbrush and state of the palette, we create an illusion where a colored trace of light flows out of the brush and falls onto the projected surface (see Figure 3).

The color of the path, or other colors drawn on the path, determines the behavior of the robot when driving over that part of the path (see Figure 1). If a line is formed by multiple colors, the robot will change its behavior as if the color directly below the robot changed the behavior. The mapping is as follows:

- Green: "Dance" -- A fun and buoyant dance that uses all the degrees of freedom of the robot.
- Yellow: "Fear response" - Tofu leans back and looks around in an expression of fear or shock.
- Orange: "Think" – A behavior where Tofu alternates between leaning left while looking to upper right, and leaning right while looking to upper left.
- Purple: "Squash and stretch" -- Tofu cyclically squashes up and down as if to bounce.
- Red: "No no" – a rapid shaking of its head from left to right.
- White: "Yes yes" – A rapid leaning forward and backwards in a whole-body nodding motion.

Figure 3: Using the digital paintbrush to "paint" a trace of light on the floor. This defines a path for the robot to navigate round two obstacles.

As a point of comparison, we also implemented some game console-like interfaces where children could remote control the robot's behavior like a video game avatar. Using our *GamePad* interface, children and control the path of the robot using joystick control. Pressing different colored buttons on a *ButtonBox* interface allows children to control the expression of the robot. By separating the two interfaces, collaboration is required to control the robot's mobility and expression simultaneously.

2.3 PILOT EXPERIMENT WITH CHILDREN

We conducted a pilot study with four pairs of young children to explore three key questions concerning the *DigitalPaint* interface. First, can young children successfully use the *DigitalPaint* interface to author robot behavior? Second, do children use this tool to create character behaviors to support imaginative story-based play? Third, what does the act of authoring the robot's behavior look like? Namely, do children collaborate to create these behaviors; is there evidence that these interfaces support what Papert calls "body syntonic learning" (i.e., when representations are coupled with movement, learners can then relate the representation to their sense and knowledge about their body); or are there opportunities for computational thinking?

Each dyad was a pair of siblings ranging in age from 3 to 8 years old. We wanted the children to be very familiar with each other so that they might collaborate when learning about and playing with the system.

- *Group 1:* Two brothers age 4 and 6.
- *Group 2:* Two sisters age 3 and 6.
- *Group 3:* Brother, age 6 and Sister, age 8
- *Group 4:* Brother, age 6 and Sister, age 8

2.4 Study Format

Tofu was introduced to each dyad along with other objects including plush toys, a ball, a toy robot, and a cardboard house made from a box. These toys could serve as props or other characters in the play scenarios. During the activities of the study, we introduced the children to the three interfaces. When using the *DigitalPaint* interface, we relied on a Wizard of Oz strategy to make sure the robot's behavior matched the child's intention. The activities are as follows:

Welcome to the Play Space. First, the children were welcomed into the mixed reality space where the experimenter described play space and introduced the props.

Introducing Tofu. Next, the experimenter brought out the Tofu robot and said: *"Would like to meet a friend of mine?"* Tofu would remain stationary except for movement in the eyes, controlled by a second experimenter using the *GamePad* interface. In this way, Tofu was established as a real-world interactive character.

Introducing *DigitalPaint*. Next, the *DigitalPaint* interface was introduced as a way to interact with Tofu through painting on the ground with light that Tofu could see. The Digital Paintbrush was given to one of the children and shown how to paint a light trace on the ground. This was often met with great excitement.

Figure 4: (Left) One of the older dyads collaboratively using the *DigitalPaint* interface to choreograph the robot's behavior. (Right) Using the *DigitalPaint* interface to have Tofu come out of his house to meet a "friend."

First Activity. The children were then asked to help Tofu find his way back to his home (the large cardboard house). Each group was allowed to try to draw a line to help Tofu find its way home. Participants were also encouraged to explore the different capabilities of Tofu and the painting interface and to play around freely with it.

Second Activity. Finally, the experimenter introduced and demonstrated the *ButtonBox* and *GamePad* interfaces as alternate ways of controlling the robot's behavior in a more remote-control fashion. Children were allowed to then play with this method of control.

3. EARLY OBSERVATIONS & LESSONS LEARNED

Observations made during these initial exploratory studies have inspired many design directions and ideas on interaction design for children.

3.1 Imaginative Play and Engagement

In this study, children were not prompted to come up with their own stories for Tofu. Rather, they were asked to help Tofu in some way (find his way home). The children did anthropomorphize Tofu and would often describe its behavior in terms of goals, emotions, and desires. They related to Tofu as a character, even imitating it at times. We also observed some spontaneous situations where children would use the *DigitalPaint* interface to have Tofu interact with other objects as characters or Tofu's toys. In one situation, an older sibling used the *DigitalPaint* to guide Tofu out of his house to meet a "friend" – a plush toy (see Figure 4 [right]). The younger sibling saw this and immediately took a ball and placed in on the floor for Tofu to play with. He then used the *DigitalPaint* interface to draw a path where Tofu would "kick" the ball. The ability of each group to acknowledge Tofu's "home" as a large cardboard box suggests that children did engage with Tofu, the box, and other toys as an act of symbolizing [14] and there is evidence that children incorporate these tools into imaginative play.

3.2 Programming and Choreography

Each group of children was able to iteratively discover the link between the *DigitalPaint* interface and movement of the Tofu robot. The discovery of the affordances of the *DigitalPaint* interface involved a clear "diving-in" and "stepping-out" cycle for the children. Each time the participant would alternate between immersion and reflection [15], new insights were gained about the system. Even though some of the participants had trouble determining the optimal way to operate the painting interface, each was able to use the system with proficiency through a process of reflection.

Using *DigitalPaint* as a tangible interface, children successfully choreographed the motion and expression of the Tofu robot. In general, children found the link between the motion of the robot and the painted line intuitive (the one exception was the 3 year old). However, the link between the color of the line and robot's expression was not recognized, but perhaps having the children explicitly vary the color of a given trace in an alternative set of tasks would have made this link apparent. Or perhaps by framing an activity explicitly as an authoring activity where the child is asked to create a theatrical performance or to choreograph a dance for the robot may make it easier for children to see the connection from color to expression.

There could be opportunities for basic aspects of computational thinking with respect to sequencing behavior, observing cause and effect, and possibly other aspects of control flow. In one instance, the 4 year old drew a closed loop in red. Tofu consequently went around and around. His older brother laughed and commented that Tofu did not know when to stop. At that moment, the 4 year old changed the path color to black and broke the loop (edited it by erasing). This is encouraging as it also suggests collaborative "debugging" of behavior may be possible. We often saw children working together to author the robot's behavior. For instance, in

Figure 4, one child draws the path and the other selects the color as they round around together.

3.3 Mimicry and Syntonic Learning

We observed instances of mimicry and syntonic learning as well. In general, the mimicry behavior appears to be inspired by the movement of the robot. This suggests, to a certain extent, the potential for body and ego syntonic learning as described by Papert [3]. In the *TofuDraw* system, syntonic learning through mimicry of the Tofu expressive robot is predicted to be a method of learning the mappings of control interfaces and understanding them with one's body. Although this potential link was observed in the *DigitalPaint* interface, which by design engages body motion, similar mimicry behavior of the robot was observed while using the *GamePad* controller as well.

For instance, during one interaction, one sister activated the "Dance" behavior on Tofu using the *ButtonBox* while her brother directed the robot to move across the floor using the *GamePad*. While the robot danced and moved, the younger brother began to mimic the behavior of the robot by dancing back and forth in a similar fashion as Tofu. When Tofu stopped dancing, he also stopped dancing. Likewise, we see similar examples with the *DigitalPaint* interface. The participant in a younger dyad had progressed from dropping small blobs of paint to laying down lines to direct the robot's motions. In one observed case, the participant moved his body back in forth in a rhythmic fashion while walking through the space and painting the line instruct Tofu's expressive motion.

We observed a significant difference in overall physical activity between the two interfaces. The *DigitalPaint* interface encouraged more physically active play. Children used their bodies much more and moved through the entire play space in the act of programming with the *DigitalPaint* interface. They tended to stay in one location and be more sedentary when using the *ButtonBox* with the *GamePad* interfaces.

4. CONCLUSION

Through the use of different interfaces – some map directly to the robot's behavior in real-time, while the *DigitalPaint* interface is used to create an editable abstraction of the robot's behavior – even preschool age children have demonstrated an ability use these interfaces. Although exploratory in nature, these first findings are encouraging, and it seems possible that the *TofuDraw* system could be used as a technology for engaging in new kinds of story-based play activities such as designing robot puppet performances that also have the potential for body and ego syntonic learning, collaborative authoring, and early forms of computational thinking.

Our next steps are to explore young children's ability to understand the "choreography painting" as an editable abstraction of the robot's behavior, and to expand the abilities of the *DigitalPaint* interface to create more interesting "programs" while more richly supporting operations such as sequencing, branching, iteration, etc. We will also add more flexible "editing" interfaces such as copying and pasting sub-drawings of the "program." Overall, this pilot offers promise that young children can use these tools and understand these abstractions. Children were highly engaged, physically active, and very excited to use the *DigitalPaint* interface to create their own robot character behaviors for new contexts. The extent of this is the subject of future work.

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