TofuDraw:
Choreographing Robot Behavior through Digital Painting

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B.S. in Electrical Engineering, University of Washington, 2007

Submitted to the Program in Media Arts and Sciences, School of Architecture and Planning, in partial fulfillment of the requirements for the degree of, Master of Science in Media Arts and Sciences at the Massachusetts Institute of Technology

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Abstract

In this document, TofuDraw is introduced as an expressive robotic character with interfaces that enable children to choreograph robotic behaviors through controlling both physical motion and form. Unique to the TofuDraw system is the presented "Digital Painting" interface, which enables children to choreograph the motion and form of an expressive robot through coloring a digitally projected surface using the affordances of painting. Additional interfaces are also presented, which enable children to control the robotic character in a realtime fashion using more traditional video game inspired control. Using these interfaces, the TofuDraw system intends to animate expressive robotic characters serving as transitional objects that allow children to explore a microworld where theater is the primary language. Evaluations of the TofuDraw system with children ages 3-8 suggest that children can incorporate the presented expressive robotic characters into their fantasy play patterns and control the expressive robot's behavior through numerous control interfaces designed to choreograph both form and motion.

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TofuDraw:

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Prologue

This thesis began with a question: can the animation techniques used to bring characters to life on the screen be used to bring robotic characters to life in the real world? From this question, I developed Tofu, a small expressive robot that uses animation techniques to appear alive. From early steps taken with Tofu, other robotic characters have been made, as well as interfaces that allow children to choreograph the behavior of these expressive robots. In these pages, I document the design of Tofu and related interfaces and discuss the potential of the system as a unique way of enabling a suspension of disbelief, which children can control. In this work the suspension of disbelief is provided by a robotic character that comes to life in the real world. Control over the character is enabled by providing interfaces that allow children to choreograph robotic motion and form.

1 Introduction

TofuDraw incorporates elements of artistic expression, theater, programability and controllability into a set of interfaces that allow children to invite expressive robotic characters into their fantasy play. TofuDraw was designed to serve as a link between the physical world and the world children imagine.

1.1 TofuDraw User Interaction Overview

TofuDraw is composed of a mobile expressive robotic character and interfaces, which allow children to choreograph the form and movement of the robot. The design of the robot enables the robotic character "Tofu" to move in different fashions which appear as distinct expressions. Interfaces designed for Tofu include mechanisms for controlling the character in real-time through use of buttons and joysticks connected to Tofu wirelessly. Other more advanced interfaces allow children to control the robot by painting a path for Tofu to follow, where the painted path controls the robot's motion and the painted color controls the robot's expression.

To use TofuDraw, children use one of the possible interfaces to bring the character to life. When using the "Digital Painting" interface, the floor can be painted and erased using a special brush and palette, giving the illusion of painting with a digital projection. By using this type of digital interface, the colorful lines can be quickly drawn, edited, and erased. To interact with the Tofu robot, children draw a line in front of the robot to indicate a path for the robot to follow. After the child finishes drawing the path, Tofu follows the line on the floor. Each color used as a path causes the robot to display a different expression when moving along the line.

By using the alternate interface of the ButtonBox and Gamepad controller, children have the ability to control the robot in realtime. The Gamepad controller changes the robots motion, while the ButtonBox allows children to change the robot's expressions at the press of a button.

1.2 TofuDraw Intended Educational Contribution

By using expressive robots and choreographic interfaces, as used in the TofuDraw system, we hope to invite children to explore intriguing ideas on safe ground. Such enactments, we claim, are co-evolutive of language and story-telling, and paramount of intelligence itself: By doing-as-if and playing-what-if, the young child learns to establish a dialogue between what "is" and what "could be", between the actual and the possible. Our purpose is to expand existing puppeteering, little theaters, and other performative environments by varying the degrees of control and immersion of the children at play. We offer new ways to move in-and-out of character, to take on different roles or perspectives, and to "animate" and drive characters (puppets) that are more or less responsive.

1.3 Thesis Overview

In the following pages I will discuss both the design and educational implications for the TofuDraw system. TofuDraw was designed as a set of interfaces which allow children to choreograph the behavior of an expressive robotic character named Tofu. The design sections will try to convey the influences and design principles which went into the TofuDraw system. The design and educational goals for the TofuDraw system stem from from a child's constructivist learning.

Ch1. Motivation will begin by describing some of the expressive character and animation-based inspirations for the characters used in the TofuDraw System. Educational technologies that have inspired the interfaces designed for TofuDraw will also be discussed.

- Motivation

- Background and Related Work

- Early Design Studies

- TofuDraw System Design

- TofuDraw Engineering

- Studies with Children

- Educational Implications

- Future Work With TofuDraw

Ch2. Background and Related Work used to design the TofuDraw system includes many different fields of research. This section will outline how the various fields have shaped and influenced the work.

Ch3. Early Design Studies will describe the ideation and prototyping process which lead to the current TofuDraw system.

Ch4. TofuDraw System Design describes the different components of the TofuDraw system as well as the systems created as precursor to TofuDraw. The operation of each device will be described in relation to choreographing robotic behavior.

Ch5. TofuDraw Engineering will be overviewed to better understand the design constants and challenges involved in creating a system like TofuDraw. An exhaustive view of the engineering will not be covered as it is not the primary focus of the thesis.

Ch6. Studies with Children will describe two studies performed with expressive robots. One using a robot to act out the stories children generate verbally and another evaluating how children interact with animated robotic characters using specialized user interfaces.

Ch7. Educational Implications will describe the ways in which the TofuDraw system could be used as a way to enable children to engage in role-play activities using expressive robotic characters.

Ch8. Future Work With TofuDraw will describe some of the ways in which expressive robots and interfaces to control them could be used in the future to enable role-play activities.

2 Motivation

TofuDraw incorporates an expressive robotic character and interfaces that enable children to control the character. Although I have approached this project from an engineering background, my intent has not been to design an optimal system from an engineering perspective but to see how engineering elements can be molded to create an experience. Many influences have been incorporated into Tofu and the related robots, as well as the interfaces which have been designed to control them. This section describes some of these influences and the ways in which they have shaped the current system design.

2.1 Animation Techniques

At the core of this thesis project is a set of robots designed to create a suspension of disbelief in those who interact with the robots. Three different robots were created to explore this effect, each with different capabilities and features. To create robots that appear more life-like, I began by looking for inspiration in animation techniques that have been used for decades to bring two dimensional characters to life. In regard to the act of animating, Norman McLaren describes the process in this way:

> *"Animation is not the art of drawings that move but the art of movements that are drawn."*
>
> \- Norman McLaren

I began by looking for inspiration in animation techniques that have been used for decades to bring two dimensional characters to life.

Although there are many ways to look at animation, one method is to see it as a reduction, or distilling, of what we see in the physical world into the core elements of a character or object. The real power manifests when this reduction comes to life through suspension of disbelief - the willingness of an observer to overlook the limitations of a medium.

Animation principles must be a core design constraint, which influences every design decision, not an afterthought.

To use animation techniques effectively on what would become the Tofu and related robots, simply using animation principles to control the robot's motions would not be enough. Animations on the screen start with a motion and take shape in a series of drawn images. Animation in robotics also starts as a motion, but takes shape through the medium of mechanics, electronics, and software. Given this viewpoint, animation principles must be a core design constraint - which influences every design decision - not an afterthought.

Many animation influences have shaped the design of the Tofu, Mochi and Miso robots. The classic animation reference *The "Illusion of Life"* [Tho81] has been incredibly helpful in understanding the animation process and classic techniques such as "squash and stretch," used to achieve "the illusion of life." The full set of twelve animation techniques described in the classic text include: squash and stretch, anticipation, staging, straight ahead action and pose to pose, follow though and overlapping action, slow in and slow out, arcs, secondary action, timing, exaggeration, solid drawing, and appeal. As a modern translation of the classic animation techniques used in the Illusion of life, Pixar's John Lasseter wrote a paper [Las87], describing how the original animation techniques could be used to animate characters and objects in 3D rendered environments.

Robots must adhere to the laws of physics, making design decisions not just a choice of appearance and aesthetics, but also mechatronic design feasibility.

When translating animation techniques to expressive robot design, one very important difference exists between the classic animation medium and robotics. Robots must adhere to the laws of physics, making design decisions not just a choice of appearance and aesthetics, but also mechatronic design feasibility. As an engineer, I have attempted to assemble a set of design principles informed by animation theory that can be used to inform the design of expressive robotic characters. The following design principles have been generated by studying classic animation texts such as *The Illusion of Life and* also by interviewing modern Pixar Studios animation experts [Pix10], who use a much wider range of methods beyond the classic techniques.

Deliver on Expectations

When speaking with animators, both 3D and 2D, delivering on expectations was found to be a common goal. The form of a character greatly determines the affordances that it provides; influencing the perceived function of the character. A form similar to an animal, such as a dog, implies the ability to do things dogs can do. By creating very simple characters that are highly expressive, the characters appear much more capable by over delivering on expectations. As an example, the Tofu robot does not have arms or legs, in an effort to avoid setting the expected functionality of the robot to an unachievable level.

The form of a character greatly determines the affordances that it provides; influencing the perceived function of the character.

Squash and Stretch

Out of the fundamental animation principles described in *The Illusion of Life*, Squash and Stretch is regarded by the authors as the most important principle [Tho81]. For an object to "squash and stretch", it simply widens out when pushed down, or more accurately, conveys a conservation of volume. This technique is not traditionally used in robotics design, but is one of the most common, if not the most common technique used in animation. Tofu and related robots use an actuated compressive foam body to achieve this effect. Ridged body forms can also create the effect by creating a link between squashing and stretching motions - a good example being the Pixar lamp, which becomes wider when compressed shorter.

Squash and Stretch is one of the most common, if not the most common technique used in animation.

Secondary Action

Animators use the Secondary Action technique to illustrate cause and effect relationships found in natural systems. A classic example of the technique is animating a horse's tail motion in response to the horse's primary body motion. In animation, the effect is generated to simulate a natural system. Since robots are an actual natural system, the effect is quite easy to generate. By using low mass aesthetic coverings, such as feathers, the effects of secondary action are

Since robots are an actual natural system, the effect of secondary action is quite easy to generate.

magnified. For this reason, the Tofu robot and related robots use feather based aesthetic coverings.

Dynamic Eyes

Animators use eyes as a powerful way to express very subtle emotions in animated characters. Eyes used by animators can be as simple as a circle with a dot to symbolize the pupil. As a design experiment, the Tofu robot and related robots were given screens for eyes. Screens are much smaller and simpler in comparison to actuated alternatives. Eye movements made with screens are also much more dynamic than what is often possible with mechanically actuated eyes.

Screen based eyes are much smaller and simpler in comparison to actuated alternatives.

The Illusion of Thinking

When speaking with professional animators about creating the "illusion of life," I viewed the animation process as the display of emotion over time. Although this is somewhat true, animators informed me that emotion without the "illusion of thinking" can create characters which appear to be zombies... The illusion of thinking is largely created by the behavior of the robot in the context of its surroundings, but it can also be influenced by emulating subtle cues found in natural systems. These include looking up when contemplating as well as actions perceived as thinking, such as dogs cocking their heads. Small timely expressions like blinking can also be used to suggest the presence of a cognitive process.

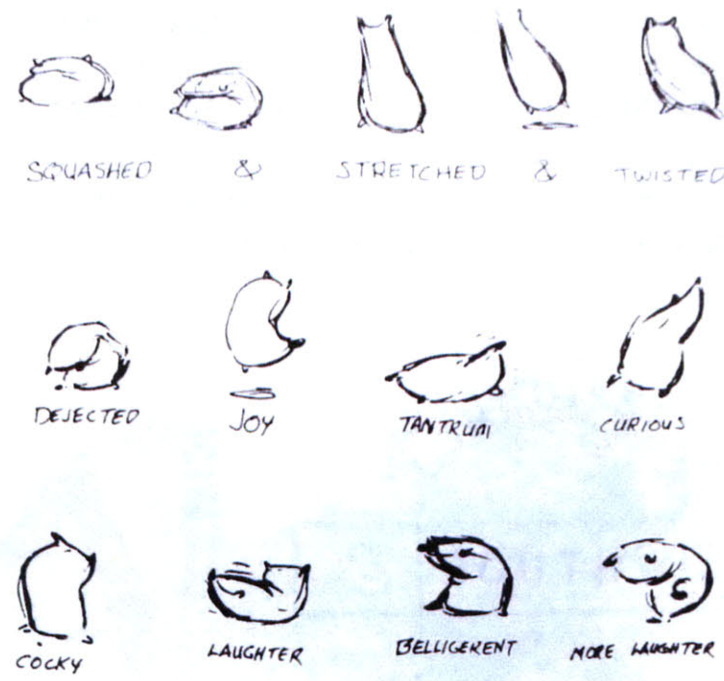
Emotion without the "illusion of thinking" can create characters which appear to be zombies...

Body Language

As an exercise at Disney Studios, animators would commonly sketch everyday objects in new ways to have the objects express emotions such as scared, excited, or laughing. A common object for this exercise being a half-full sack of flour [Tho81]. Building on the illusion of thinking, a powerful way of creating life-like robotic characters is to provide simple ways for the characters to present body language. One common example of body language for animated characters is engagement. By leaning forward and looking at an object with both its, eyes and head position, a character can demonstrate that an object is not just thought about, but is actually

A powerful way of creating lifelike robotic characters is to provide simple ways for the characters to present body language.

engaging. Similarly, leaning back with a fixed gaze can convey a sense of uncertainty or surprise.



To develop simple yet powerful forms of visual communication, Disney Studios animators would commonly animate everyday objects such as a sack of flour.

2.2 Art and Design influences

The aesthetic form of the Tofu robot and related robotics characters has been heavily inspired by a number of art and design influences. One of the most inspirational influences come from the work of Japanese animator and director Hayao Miyazaki [Miy10]. Miyazaki's work includes incredibly simple yet powerful characters.

The characters from Hayao Miyazaki's film have had a strong influence on Tofu and related robotic characters.

Other design influences for Tofu and related robotic characters come from the universe of Jim Henson [Hen10]. Henson's legacy as a puppeteer is widely acknowledged through his contribution to productions such as the Muppets and PBS procedure Sesame Street. Henson is considered one of the most widely known puppeteers in history. The characters used in Henson's productions have been a major influence on my work, both in terms of the aesthetic considerations for characters and the personality used to bring characters to life.

The lovable characters designed by Jim Henson Studios have influenced the feel of Tofu and related robotic characters.

3 Background and Related Work

TofuDraw was designed to serve as a link between the physical world and the world children imagine. The design of the TofuDraw system is influenced by many research fields, each of which have played a different role in shaping the current implementation of the project. Within these areas of research, specific related works have also been influential in shaping the current state of the project. This section describes these different areas of research and their influences. At the end of this section, the specific unique intended contributions will be described in the context of related work.

3.1 Tangible Media

Although not all aspects of the TofuDraw system can be considered a Tangible Interface [Ish99], the philosophy of tangible interface design has influenced many design decisions in the development of the TofuDraw system. Creating an experience which engages multiple senses was identified early as a desired component for the TofuDraw system. One reason for creating a physical experience using expressive robotic characters was to make systems that inherently support kids' pretend and role play by existing in a shared space, by being immersed together. Other motivations originate in benefits found using tangibles in supporting both exploratory and expressive interactions in a play setting [Pri03]. It is not the same to drive an avatar in a social virtual environment using a mouse or a keyboard, or to remotely control a vehicle in the real world. And when playing together, it matters who is in charge of what (how many "puppeteers" and how responsive the puppets), and how kids can negotiate rules and roles.

It is not the same to drive an avatar in a social virtual environment using a mouse or a keyboard, or to remotely control a vehicle in the real world.

3.2 Programming by Demonstration

The robot demonstrates the program, allowing children to reflect on the motion described.

Interfaces designed to control the TofuDraw system have been inspired by projects designed to be programmed by example. Such systems invite users to demonstrate the desired output to the interface as instruction. One such system, Topobo [Raf04], is a construction kit with kinetic memory that invites young children to build spatial creatures and program their movements by directly twisting and turning the physical model. By physically manipulating the behavior of a structure made with Topobo units, children can program the structure to move. Another example of programming by example is CurlyBot, which is a small wheeled robot that can be moved on a surface. Movements can then be played back, allowing users to reflect on the motion of the robot. When using the "Digital Painting" method to control the TofuDraw system, users are also able to physically describe the motion of system - although the description is still an abstraction of the actual motion. The robot then demonstrates the program, allowing children to reflect on the motion described.

3.3 Programming in the Physical Environment

It is hoped that children do not just use and understand the programming interface, but also "become" the interface by using it in a physically engaging way

A major component of TofuDraw is the ability to control a robotic character's behavior through a drawing process. This process could be described as "programming by tracing or marking". Programming is not the objective of the system, but rather providing a controllability to children enabling them to use the technology as a means to improvise or construct a narrative performance of the go. This expression is paramount to the overall design and has been used as a lens to try to envision engaging interfaces to enable expression.

By programming the behavior of the Tofu in the physical environment, a connection has been sought that connects the act of programming to a physical motion. By creating a means of programming that is at the core a form of motion, it is hoped that children do not just use and understand the programming interface, but also "become" the interface by using it in a physically engaging way.

A further motivation for creating a physically situated method of choreographing the behavior in the TofuDraw system stems from work on embodied cognition, which supports the idea of a bodily or kinesthetic intelligence [Gar83]. In his work on multiple intelligences, Howard Gardner offers the components of Bodily-kinesthetic intelligence: the ability to manipulate objects in a skilled manner and masterful coordination of one's body movements [Gar83].

Two related research projects have been inspirational and influential in shaping the direction of this work. The first uses physical markers to program the behavior of a small vehicle. The work is described as "Ambient Programming" which makes programming more accessible by spreading a program throughout a physical setting, making the act of programming a physical one. An example of this type of programming uses robotic vehicles that are programmed by placing cards in front of the robot [Eis09]. These cards dictate the robot's movements when the robot moves over cards that contain a special marker mapped to the cars behavior. Twinkle, is another example of what could be called "Ambient Programming" and uses color as a means of programming in the physical environment. Instead of using cards as a special marker, color is used, allowing for programming where anything to be used as a color [Sil10].

3.4 Symbolizing and Engaging the Absent

TofuDraw intends to create a link between what can be seen and what the imagination provides. The physical character "Tofu" is designed to serve as a participant in the playful activities of children by providing an anchor in the physical world and at the same time an element in the world of fantasy. Although the Tofu robot is only moving across the floor, the act of moving across the floor allows a child to imagine Tofu crossing a rickety rope bridge. This scene exemplifies symbolizing: a creation of a lived-in space in which the absent is made present and the ready at hand [Nem98]. By existing in both the real and the fantasy world at the same time, Tofu

By existing in both the real and the fantasy world at the same time, Tofu provides a means of creating a dialog between what is and what could be.

provides a means of creating a dialogue between what is and what could be.

3.5 Role-play as a form of Pretence

Pretence, or suspension of disbelief, is at the heart of human imagination, and imagination constitutes the inner face of creative expression.

As mentioned in the thesis overview, pretence, or suspension of disbelief, is at the heart of human imagination, and imagination constitutes the inner face of creative expression. Like simulation itself, make-believe activities (simulacre, in french) provide players with a safe ground to revisit and re-enact otherwise intriguing or risky ideas on secure ground. Pretence appears around the age of two, when infants start cuddling a doll or drinking out of empty cups. Well-formed pretence scenario involving complex narratives is unlikely before the ages of four or fove[Ack10].

Role-play is a specific form of pretence in which the player assumes or is given a role to play. Through it, a person experiences things through the eyes of others and learns to simultaneously stage and play out aspects of her own and other people's ways of being, doing, and relating. In their role-play, very young children "become" tour a tour a baby or a mom, a cat or a dog, a scary monster or a monster-robot. These abilities appear around the age of two, culminate at the ages of five or six, and diminish prior to adolescence to reappear again, as adult art forms (as in theater, puppet-shows, art performances) [Ack10].

Through pretense and role-play, children get a chance to revisit, enact, and dramatize many intriguing events, sometimes changing the original event's outcome, and sometimes changing their own persona— all of which helps recast (and yes, bend) "reality" to serve one's needs, fit one's dreams, and come to grips with some of the hardships that growing up entails. Early manifestations of make-believe appear around the age of two, when children engage in activities like feeding and talking to their dolls, ride chairs, and pretending to be a lion [Ack10].

3.6 Technologies for Fantasy Play and Storytelling

Storytelling has been shown to play an important role in the development of children's creativity and cognition. By telling stories, children are practicing representing events in narrative form that can be shared with others [Bru97]. They also explore different outcomes of different events and negotiate the meaning of those events with others [Dys93]. When children practice storytelling it also gives them an opportunity to practice symbolic manipulation, and hold multiple abstract concepts in their head [Pel91]. As a tool to help children engage in dramatic play and storytelling activities, TofuDraw has been designed as a mechanism, that can potentially supplement existing benefits of storytelling.

TofuDraw has been designed as a mechanism, which can potentially supplement existing benefits of storytelling.

Through expressive characters, TofuDraw strives to create technologies that complement the fantasy play patterns that children already have. In one such research project, StoryMat, children participate with what is described as a computational system that engages in story listening rather than story-telling. StoryMat becomes a part of children's fantasy play by recording and recalling children's narrating voices, and movements made with stuffed animals [Cas01].

Robots have been used as part of a mixed physical and digital authoring environment for children where stories can be augmented by robots controlled by children [Ryo09]. In this scenario, robotic characters were integrated into a story environment though a screen based user interface that enables children to program robotic character behaviors. The programmed behaviors are then linked to a drawing made by the user. Through the use of robotic characters, programming, and drawing, children were able to create stories which unfold in a creative way.

3.7 Transitional Objects and Theater as Microworld

The Tofu robot in the context of the TofuDraw system, strives to become for children what Winnicott considers a transitional object [Win53] and what Papert coined as an "object-to-think-with" [Pap80]. In Papert's view, such a transitional object or object-to-think-with, allows children to make sense of tasks in terms of everyday familiar experience but supports them in moving into the world of the abstract. One of the strengths of transitional objects, in Papert's perspective is their ability to be a part of a child's microworlds. Microworlds can be described as a learning environment or tiny world, where children can explore alternatives, test hypothesis, and discover facts that are true about that world. A famous example of such a transitional object, or zone, in a microword is the Logo Turtle [Pap80], which invites children to explore a world of mathematical concepts. By creating objects such as the Logo Turtle that perform in the real world as well as the microworld created around them, they become a powerful link between what is and what can be.

Microworlds can be described as a learning environment or tiny world, where children can explore alternatives, test hypothesis, and discover facts that are true about that world.

As with the Logo Turtle, Tofu in the context of TofuDraw strives to become a transitional object that opens up a miroworld for children. The Logo Turtle lives in a world where mathematical concepts are not abstract but one as real as the Turtle itself. The Turtle speaks in the language of mathematical concepts and programming. Tofu in the context of TofuDraw lives in a world of theater, where the language spoken is expression and movement. To enter into this world, children choreograph the movements and expressions of the robot through interfaces which "speak" the language of the microworld, a language of movement and expression.

Tofu in the context of TofuDraw, lives in a world of theater, where the language spoken is expression and movement.

3.8 Constructionism and Learning

Constructionism is both a theory of learning and a strategy for education that is rooted in Piaget's constructivism [Pia71], in which learning is characterized by an individual cognitive process given a social and cultural context. Constructionism proposes that people learn more effectively when provided with opportunities to design, create, and build projects that are personally and epistemologically meaningful [Pap80]. TofuDraw is built on a constructionist's approach to learning by

Constructionism proposes that people learn more effectively when provided with opportunities to design, create, and build projects that are personally and epistemologically meaningful.

giving children tools to produce and manipulate personally meaningful artifacts.

Starting with the LOGO programming language, many computational tools and environments have been made with the ability to engage children in the construction of personally meaningful projects through programming [Bru97, Mal04, Res96]. Some have been explicitly designed to facilitate children's exploration of storytelling [Ber99]. Programming is often depicted as a top-down, divide-and-conquer technique; however, Turkle and Papert argued that there may be more a "soft" approach to programming modeled after bricoleurs, who arrange and rearrange to construct meaning with a set of familiar materials [Tur90]. Through negotiation and association, Bricolage organize work by playing with elements as they would in a collage. TofuDraw aims to provide a flexible and familiar programming space where children are free to play with the choreography of expressive robotic characters through the act of painting with a digital medium.

Turkle and Papert argued that there may be more a "soft" approach to programming modeled after bricoleurs, who arrange and rearrange to construct meaning with a set of familiar materials.

3.9 Unique Contribution

By using expressive robots and choreographing interfaces, as used in the TofuDraw system, we hope to invite children to explore intriguing ideas, on safe ground. Such enactments, we claim, are co-evolutive of language and story-telling, and paramount of intelligence itself. By doing-as-if and playing-what-if, young children learn to establish a dialogue between "what is" and "what could be", between the actual and the possible. To facilitate such interactions, we introduce the TofuDraw system, which aims to create a link between what can be seen and what the imagination provides. "Tofu," an expressive robotic character, is introduced as a participant in the playful activities of children by providing an anchor in the physical world that can also be an element in the world of fantasy.

By doing-as-if and playing-what-if, young child learn to establish a dialog between what is and what could be, between the actual and the possible.

We offer new ways to move in-and-out of character, to take on different roles or perspective, to "animate" and drive characters that are more or less responsive. With the TofuDraw system, users choreograph the behavior of a robotic character through tangible interfaces in the physical environment using the "Digital Painting" technique presented. By programming the behavior of the Tofu robot in the physical environment, a connection has been sought, that connects the act of programming, or choreographing, to a physical motion. By creating a means of programming that is at the core a form of motion, we posit that children will not just use and understand the programming interface, but also "become" the interface by using it in a physically engaging way.

Our purpose is to expand existing puppeteering, little theaters, and other performative environments by varying the degrees of control and immersion of the children at play. By providing children with an expressive medium to choreograph robot character enabled performances, we hope to supplement existing benefits of storytelling within a constructionist learning environment. We aim to provide a flexible and familiar set of interfaces that enable children to engage in a Bricolage approach to programming, where children are free to play with the choreography of expressive robotic characters. Through such interactions, Tofu, in the context of TofuDraw strives to become a transitional object, opening up a miroworld of theater for children. A microworld where the language is that of movement and expression.

4 Early Design Studies

The original conception for Tofu as a robotic character was not limited to the current project implementation, but was rather an exploration into designing expressive robotic characters for a young audience. This section will overview the conceptual framework for designingTofu as well as the current TofuDraw system.

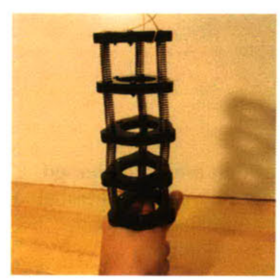
The goal was to create an expressive and simple robot for a young audience.

4.1 Why Squash and Stretch?

The primary goal for Tofu as a character was simply to create an expressive robot character that is optimized for simplicity and expressiveness. During the early design for Tofu and later robots inspired by Tofu, squash and stretch was identified as a powerful expressive quality for a robotic character. This design direction was inspired by the nearly ubiquitous use of the squash and stretch technique in 2D animated characters. In principle, the technique is quite simple: when an object compresses down, it expands out to convey volumetric conservation found in organic systems. By adding this effect to robotic systems, the goal was to create characters that appear to have what animators call the "illusion of life."

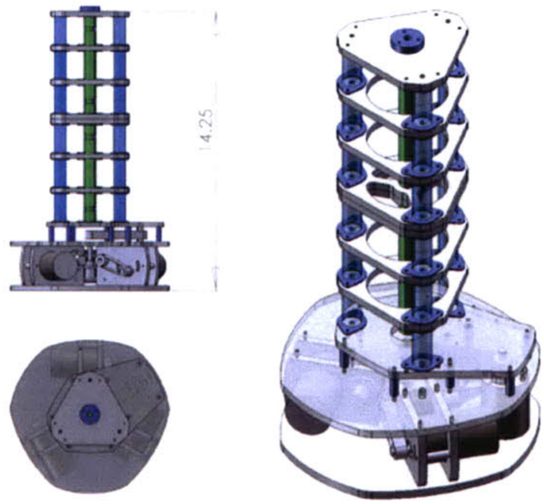
4.2 Mechanical Implementation of Squash and Stretch

In nature, the squash and stretch property is innate in many objects that change shape during motion, such as muscles. Robots do not typically share this quality, due to the non-biological nature of robots. For Tofu, the goal was to make an actuated system which can move in response to digital signals sent to the robot, to create motions which are controllable and repeatable. Early prototypes for this mechanism relied on a complex network of springs to enable the structure to compress. String running through the mechanism could then be used to controllably deform the shape of the mechanism.



Early design studies focused on mechanisms for creating mechanical squash and stretch.

Motorized winches could then be used to digitally control the position of each string.



Early CAD prototype of squash and stretch mechanism using network of springs and motor controlled strings to deform in a controlled way.

Although early tests of the spring based mechanism were functional, the complexity of the system was substantial. Following the spring based design, a much simpler design relying on bedding foam was used as a compressive section. When released, the foam restores the structure to its original position. In addition to having spring properties, the foam behaves as a mechanical damper, making motions smooth and succinct. An early prototype was made out of string and foam to test the general body motions. Instead of using motors, simply moving each string by hand was sufficient. Future versions of the mechanism use actuated strings to allow the structure to collapse in a controlled way.

Foam behaves as a mechanical damper, making motions smooth and succinct.

Sting and foam based prototype of controllable squash and stretch mechanism.

4.3 Eye Actuation Exploration

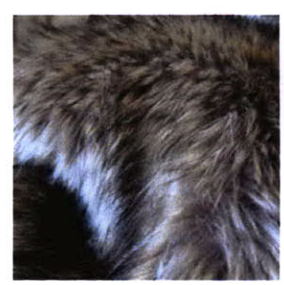
Through general observations of 2D animated characters, it was clear that dynamic eye motion is a common trait. Dynamic eye motions found in animated characters and in nature served as the motivation for Tofu and related characters. Social robots such as Kismet [Bre02] create powerful social interactions with eyes that are physically actuated using motors. Although creating a motorized eye actuation mechanism for a robot as small Tofu would be possible, the technology needed would be substantial. Instead of perusing an electromechanical method of creating eye motions, I decided to explore the use of small LCD displays based on Organic LED or OLED technology. Due to the OLED displays high contrast ratio, wide viewing angle, and ability to display dynamic motion, the displays were chosen for the eyes of Tofu and related characters.

Kismet is an example of physically actuated eyes in a social robot application.

Example of miniature OLED display used in Tofu and related robot characters.

4.4 Material Selection Exploration

Although the process of picking materials is a very broad topic when discussing design and fabrication, the selection of materials for Tofu and related robots was determined by both engineering constraints and aesthetic considerations. The main concern when determining the outer material was making the robot appear welcoming and somewhat organic. A secondary concern was to choose materials that exaggerate the effects of secondary action, or motion that is a result of some primary motion. An example of secondary action is the tail of a horse which moves in response to the horses stride. Along with Squash and Stretch, Secondary Action is another common technique used by animators to create the "illusion of life."



Early material selection tests included "Faux Fur", a fake fur made to look like real animal fur.

Early material selections included fake fur, which is sold by the yard and comes in different patterns. Although the fake or "Faux" fur was soft and welcoming, shapes made with the fur looked matted down and fixed in form. When deformed, the faux fur exaggerated the effects of movement to a degree, but still lacked the full effect of secondary action.

The second attempt in finding a fitting expressive material draws again from the animal kingdom. Instead of using heavy fur as an aesthetic covering, the next materials tried were light-weight feather based materials. Due to the extremely low mass of feathers, the visible effects of secondary action are very apparent, making them a perfect choice. Wispy and light feathers such as large ostrich feathers and feather boas were found to work extremely well as a material with secondary action.

Low mass material such as ostrich feathers were found to visually exaggerate the effects of secondary action.

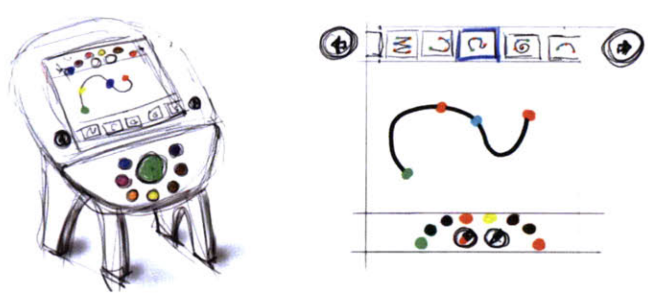
4.5 Choreography Interface Exploration

From the beginning, a major goal of the TofuDraw project has been to create expressive robotic characters and give children interfaces that allow them to choreograph the behavior of those characters. Although many different interfaces have been considered for enabling these choreographing abilities, only a couple have actually been implemented. Most of the ideation process has happened though generating concept sketches and some physical prototypes.

The first interface that I considered as a means of enabling children to control the behavior of the expressive robots was an adaptation from video game design. Instead of controlling a video game, a gamepad controller could easily be used to control the behavior of a robot. This technique has been used extensively to develop the expressive robot characters. One advantage of creating physical robots is that they exist and move in the physical environment. Although a gamepad is a very intuitive interface to learn, the use of the gamepad is relatively sedentary. In an effort to create interfaces which engage children more physically, the gamepad interface was not embraced fully.

Gamepad controllers used for video games were considered as an initial way to enable children to choreograph the behavior of robotic characters.

The second interface design conceived, incorporated elements of painting as a means of choreographing the behavior of the robots. Instead of painting on a canvas, this easel-inspired interaction method would use a touch screen. Although this method is also relatively sedentary in design, the interface links painting to robot behavior in a way that enables children to iterate and reflect during the creative process. Multiple paintings or behaviors could also be saved and replayed. In this



Painting on the touch screen of this easel-based interface could enable children to iterate and reflect during the creative process.

scenario, a line would determine a robots path and a color would determine a specific robot expression.

Lines are no longer just abstract representations for the robot's behavior, but are actual paths for the robot to follow.

The next concept and current design created takes elements of the previous painting interface and applies it to the actual environment that the robot is in. Like the easel based interface, painted lines have a mapping to the robots actions such as following lines with behavioral mappings to color. Unlike the easel interface, painting in the physical environment removes a layer of abstraction found in the gamepad interface as well as the easel interface. By painting directly in the physical environment of the robot, behaviors can be choreographed using mappings that are very direct and intuitive to the user. Lines are no longer just abstract representations for the robot's behavior, but are actual paths for the robot to follow.

Example of child interacting with a robot through painting in the physical environment. Paintings become instructions for robot behavior.

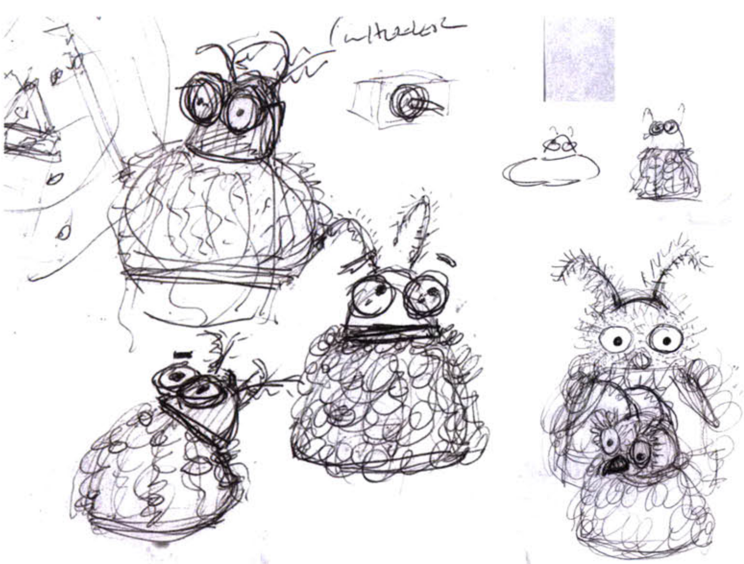
4.6 Character Design Exploration

The actual inspirations for designs are always a bit of a mystery, but the steps that lead to the design of the Tofu robot do shed some light on the deigns influences and philosophy. Early prototypes for Tofu were heavily influenced by simple yet powerful characters found in animated cartoons - in particular the characters found in films directed by Hayao Miyazaki.

The challenge was not creating characters in general, but creating characters that came to life when they were

Early prototype of the Tofu robot, inspired by the characters found in films directed by Hayao Miyazaki.

physically built. This ultimately requires the design to be influenced by not just the personality of the character, but also the feasibility of the character. Prototypes leading up to Tofu lacked this marriage between personality and feasibility. Prototypes were either a plush character with personality but no mechanized movement or a mechanism with the ability to move in an expressive way, but never both at the same time. The design for Tofu came as a step sideways, an integration of both mechanical design and personality. The original sketch for Tofu is now just an artifact of the process, but was at the time a powerful way to connect what was to what could be.



A copy of the original sketch made for Tofu's design while on the subway.

5 Usage: TofuDraw System Design

TofuDraw started as an exploration in bringing animated characters off the screen and into the real world. Using these characters, I have tried to create interfaces that allow children to project themselves into the animated characters. Interfaces which facilitate a dance between what was, what is, and what can be in a Role-play environment. In this section, I will describe a set of design principles that have been influenced by these intended interactions, and how these design principles have influenced the systems components and overall design.

5.1 Design Principles

TofuDraw was designed to be a part of the fantasy worlds children already create with objects and artifacts. Through the use of technology, we have tried to only supplement these play patterns. With this general goal in mind, a set of seven design principles have been helpful in creating the TofuDraw system.

Design Principles
- Intuitive
- Expressive
- Meaningful
- Support Exploration
- Inclusive
- Engage Multiple senses
- Robust

Intuitive - The entry point for interaction should be intrigue, which guides the user through stages of exploration.

Expressive - Ultimately the experience should be created to facilitate expression, and should itself be expressive.

Meaningful - The interfaces provided should enable personally meaningful expressions to the user(s).

Support Exploration - Ideally, intuition and intrigue are all that is required to explore the capabilities of the system, and with the capabilities of the system, explore topics that are difficult or impossible to reach outside the realm of role-play.

Inclusive - The system should support many users as a core requirement, not as an afterthought.

Engage Multiple Senses - Create experiences that engage sight, sound, and touch in a shared environment.

Robust - Fantasy play is expected to take many interesting directions, the system to facilitate these adventures should be as robust as the directions it takes.

5.2 Robot Explorations

Three different robotic characters have been made as part of the TofuDraw system. Tofu is the first of the three, and is the robot used for the primary user study. Although not all the robots have been used in formal evaluations, they are included in this section because they have been a large part of the exploration into robotic character development. In this section I will try to convey the design goals with each robot, and the major lessons learned. Each of the robots presented are puppeteered, and have no autonomous functionality. The different robots and their capabilities are as follows:

Although not all the robots have been used in formal evaluations, they are included in this section because they have been a large part of the exploration into robotic character development.

	Tofu	Miso	Mochi	Tofu and Base
Expressive	●	●	●	●
Wireless		●	●	●
Mobile		●	●	●

Multiple robotic characters were made, which have different expressive wireless and mobility features.

Tofu - Robot Character One

Tofu is the first robot character I created as an exploration into creating animated characters in the physical world. Since robots are typically conveyed in western culture as threatening automata, it was important to me to design a robot that broke these rules and associations with threatening robots. I did not want Tofu to be a tour guide of the world for children, but rather a companion that explores the world with them.

I did not want Tofu to be a tour guide of the world for children, but rather a companion which is also exploring the world with them.

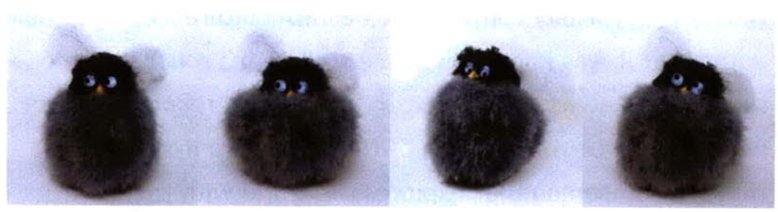
The character was given a personalty before a form. Instead of creating a character that is very sure of itself, Tofu is not too sure of anything, is easily frightened, and is alway observant. These qualities took on a form with bird influences. Soft materiality and infant proportions were used to make Tofu welcoming. The robot does not speak, but does create sounds when moving. Animation techniques used such as squash and stretch, secondary action, and dynamic eye motions, enable the character to be expressive.

Tofu is the first expressive robot made during the exploration.

What is important in the design of Tofu is not what the character can do. but what is missing and becomes complete in the imagination.

A core design requirement was to make Tofu as simple as possible. To do this, the design of Tofu is very much a marriage between personality and mechanical feasibility. Although simple systems are often more reliable, the design method of creating a simple character goes much deeper than mechanical dependability. Simplicity in design allows the character to take on a form that comes to life by providing an outline for the imagination to fill in. What is important in the design of Tofu is not what the character can do, but what is missing and becomes complete in the imagination.

Through multiple degrees of mechanical freedom and screen based eyes, Tofu can express a palette of expressions.



The abilities of Tofu are mainly in expression and are lacking in mobility. Three motors in the robot body allow for a number of expressive body motions, which can be coupled with the robot's head motor and OLED based eyes to create expressive motions such as dancing. Although the robot is very expressive, mobility is not one of the forms of expression. Tofu also requires external power and a computer to operate. A tether connects to the rear of the robot to provide power and a connection to a computer.

Mochi - Robot Character Two

Following the completion of Tofu, I wanted to explore the use of mobility, neck articulation, and reconfigurable aesthetics as expressive elements in robot character design. To do this, I built Mochi, which is by far the most complex of the three robots presented.

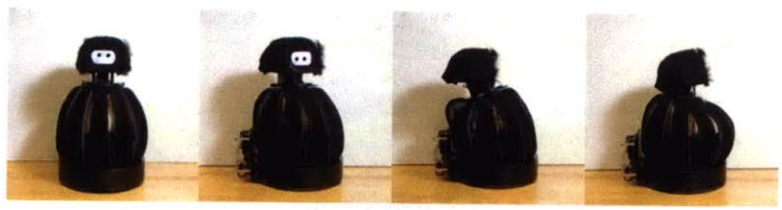
Mochi is the second in a series of expressive robotic characters and is more complicate than Tofu.

Mochi uses a special omnidrive base that can rotate and translate simultaneously. Mobility in general was found to be a very powerful form of expression for the small robot, but the use of omnidrive was not as powerful as expected. The strength of the character in many ways relies on conveying the intention of the character and its response to the same world in which we exist. When translating and rotating simultaneously, the robot appears to be spinning out or control and in many ways looses the intention it had when moving in what appears to be in a controlled and deliberate fashion.

Mochi uses a special omnidrive base that can rotate and translate simultaneously.

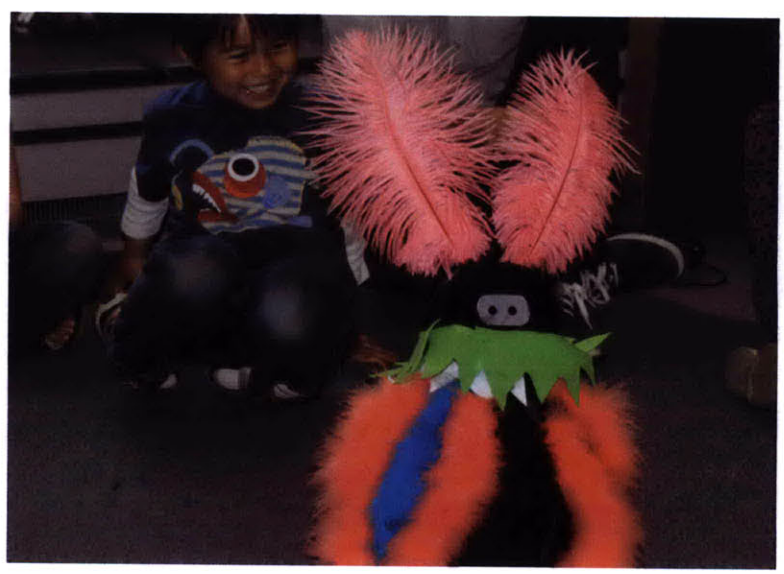
One of the powerful expressions found with Mochi came from a conversation with a Pixar animator on the power of simplified body language in animated characters. One of the core types of body language implemented with Mochi is the appearance of engagement and disengagement. By leaning forward with a fixed gaze, the robot is not just displaying a raw emotion like happy, but is instead displaying something much more rich, the interest in something it can see. Likewise, quickly leaning back while keeping the robots eyes fixed on an area of interest, causes the robot to convey surprise or perhaps epiphany. The use of this type of body language relies heavily on the robots ability to articulate its head up and down. Tofu lacks this ability and cannot keeps its head fixed on an object while leaning forward or backwards. The use of engagement through leaning forward was found to be a powerful expressive quality.

The use of engagement through leaning forward was found to be a powerful expressive quality.



Mochi can lean forward and backwards to express engagement.

In addition to mobility and head articulation, Mochi is made with an outer shell of Velcro material. This is to enable the robot to have reconfigurable aesthetics. A series of velcro coverings were created that can easily be attached and removed from the robot's body. Although the coverings are easy to apply and remove, the ability to configure the robots aesthetics seems to introduce a compromise to the robot's character. Making the robot appear complete both with and



Mochi's Velcro body allows reconfigurable aesthetics to be placed on his body.

without an aesthetic covering is difficult. When "dressed" the robot appeared to be wearing a oversized fur coat instead of part of its body. The ability to change the robot's aesthetics seems to be powerful as long as the ability does not introduce too much of a compromise. In retrospect, clothing or accessories for the robot would be a more powerful way to provide customization to the robotic character.

Miso - Robot Character Three

Miso in many ways was an attempt to focus some of the findings from Tofu and Mochi into a new robotic character. Miso combines mobility and expressiveness in a very small package. The design influences for Miso came from picturing what the offspring of Tofu would look like. Mochi as a mechanical systems was designed to do many things, and ultimately was not able to do any of them particularly well. With miso, I tried to give the robot only one or two different expressive abilities, but to execute those abilities well.

The design influences for Miso came from picturing what the offspring of Tofu would look like.

Miso in many ways was an attempt to focus some of the findings from Tofu and Mochi into a new robotic character.

Like Tofu, Miso can squash and stretch, but does so with only two motors instead of three. This gives Miso the ability to move left to right, but not forward and backwards. Two small powered wheels inside Miso give the little robot the ability to roll around. Through very informal design studies, it was found that Miso serves as a powerful character but works best when the robot can play off the expressiveness of other characters. The simplicity of Miso makes the robot's expressive capabilities not quite as rich as a robot like Tofu.

With miso, I tried to give the robot only one or two different expressive abilities, but to execute those abilities well.

Tofu Base

While TofuDraw was developed as a method for children to choreograph robotic behavior, it became clear that both robot mobility and expression would both be critical. Although some of the robotic characters are very mobile and some very expressive, none of the characters had the right combination of expressiveness and mobility. To find this combination, a special car was made for Tofu to drive around in. Both Tofu and the base are battery powered and are interfaced to a small laptop riding on the mobile base. By sending control signals to the base wirelessly, the expressions of Tofu and the movement of the base can be controlled from a distance.

The existing characters didn't have the right combination of expressiveness and mobility. To find this combination, a special car was made for Tofu to drive around in.

5.3 Robot Choreography

The goal of TofuDraw is to give children tools that let them choreograph the behavior of robotic characters in the physical environment. The ability to choreograph can be described as the ability to sequence movements that include motion and form. Sequencing the motion and form of robotic characters could be accomplished in many different ways. Based on my design principles, there are several factors which have influenced the current interfaces and interaction patterns. Since the interface should incorporate collaboration and multiple senses, a preference for tangible and physical interfaces was established over traditional screen based user interfaces. With any interface used for choreographing robot behavior, there will most certainly be some abstraction between the interface and the robots behavior. In an effort to make the system intuitive, I have tried to keep this abstraction as simple and explorable as possible. As a variable in the system design, I have designed some interfaces that control the robot in realtime, and others which control the robot after a set of motions have been choreographed.

The ability to choreograph can be described as the ability to sequence movements that include motion and form.

ButtonBox and Gamepad

The ButtonBox and Gamepad method of controlling the robot's behavior is designed to give children the ability to control the robot's behaviors in realtime. Control of the robot's motion and form are separated into two different device, the ButtonBox and the Gamepad. When using these devices, the ButtonBox is used to control the robot's form. Six different behaviors are mapped to the colored buttons on the ButtonBox. When one of the buttons is pressed, the robot will immediately start performing the corresponding behavior. The mapping of the colors on the ButtonBox to the robot's behavior are as follows:

The ButtonBox and Gamepad method of controlling the robot's behavior is designed to give children the ability to control the robot's behaviors in realtime.

Green: "Stevie Dance" - The Stevie dance is a special dance Tofu does which is inspired by Stevie Wonder.

Yellow: "Paranoia" - Tofu leans back and looks around in an expression of paranoia.

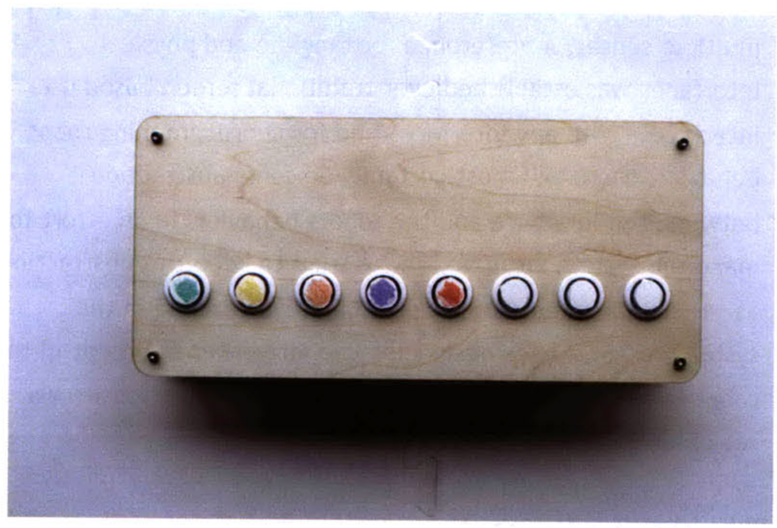
Orange: "Think" - When thinking, Tofu alternates between leaning left while looking to upper right, and leaning right while looking to upper left.

Purple: "Squash" - The squash routine is Tofu cyclically squashing up and down.

Red: "No No" - No is just a quickly panning the head from left to right.

White: "Yes" - Yes is just leaning forward and backwards in a nodding yes motion.

The ButtonBox interface allows user to control robotic expressions remotely with the press of a button.



By using the Gamepad interface, users can control the mobility of Tofu through use of a joystick on the gamepad interface. By pushing the joystick forward, the robot moves forward, likewise with backward. If moved to the right or left the joystick causes the robot to spin in place to the left or right. The angle of the joystick from the center position is proportional to the velocity of the robot. By combining left-right with forward-backward joystick motion, the robot can be directed in combinations of forward-backwards and right-left motion. This enables the robot to move in ways such as forward and veer left.

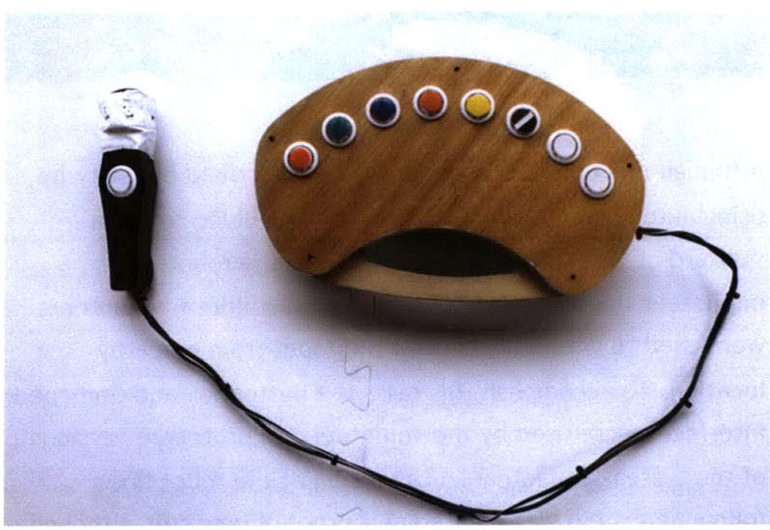
A wireless gamepad allows operators to easily control the Tofu Base from a distance.

A design feature of using both the ButtonBox and the Gamepad interface to control the Tofu robot and its mobile base, is that two people are required to operate both at the same time. By separating the two interfaces, collaboration is required to control the robot's mobility and expression simultaneously.

Digital Paint

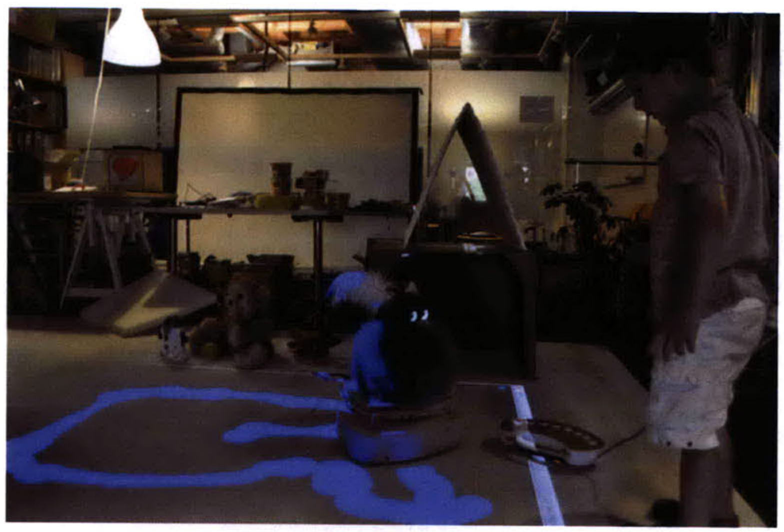
Through the use of "digital paint" I have tried to create a digital medium that can be used to control robotic characters. Controlling the behavior of robotic characters is just one of the uses for digital painting, which itself is fairly general. Like real painting, digital painting allows a user to color a surface with a brush. Instead of using actual paint, digital paint uses a digital projection to cover a surface with a specific color. By tracking the location of a special "digital paint brush" and tracking the state of a button on the paintbrush, the illusion created is paint flowing out of the brush itself and onto the projected surface. The digital paint brush is attached to a palette with a set of colored buttons. By pressing a button, a new color can be selected to paint with. In addition to the colored buttons, an erase button is also on the palette. Depicted by a black circle with a white line going through it enables an erase mode instead of painting.

Instead of using actual paint, digital paint uses a digital projection to cover a surface with a specific color.



The Digital Painting interface consists of a palette and brush.

When used as an interface for choreographing robot behavior, the digital painting technique gives a user the ability to define a path for the robot to follow. The color of the path drawn determines the behavior of the robot when driving over the path. For instance, if the trigger is pressed on the digital paint brush a blob of color will appear directly under the brush. If the brush is moved, a path of color will appear under the brush. Once the path is finished, the robot will go to the start of the path and drive over the line of color, or as one three-year-old boy named it, “a light street.” 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 of color to behavior used for the Digital Painting interface, and the possible behaviors are identical to the mappings used for the ButtonBox interface.



Although it is possible to generate the described behavior by using autonomous navigation systems, I decided to use a “Wizard of Oz” approach for controlling the robot. To puppeteer the robot during studies with children, volunteers were used to wirelessly control the robot from a nearby location. To accomplish this task, the ButtonBox and Gamepad interfaces were used by the volunteers. In prototype versions of the system, an autonomous version of the robot line following system was created as a proof of concept. Although this works well in theory, the ability to control the robot directly with knowledge of the environment gives the hidden robot controller an opportunity to create much richer interactions.

5.4 Limits of the Current System

The current TofuDraw system does not support multiple children drawing at the same time or the ability to save drawings which have been made with the system. Due to the single light source used to project the “digital paint” on the ground, shadows can occasionally form when children step between the projector and the projection surface. The sensors used to track the digital paintbrush can also become hidden from the tracking system, causing momentary blocks in tracking. Although these issues do occur from time to time, they have not been found to significantly hinder the interaction.

6 How it was built: TofuDraw Engineering

This section describes the engineering approach used in creating the TofuDraw system and the engineering constraints that define the projects limitations. The items covered in this section include three different expressive robot prototypes as well as control interfaces for the robots. In addition to the three robotic characters and control interfaces, a small robotic mobile base is introduced. The purpose of this base is to provide mobility to the Tofu robot used in the TofuDraw system.

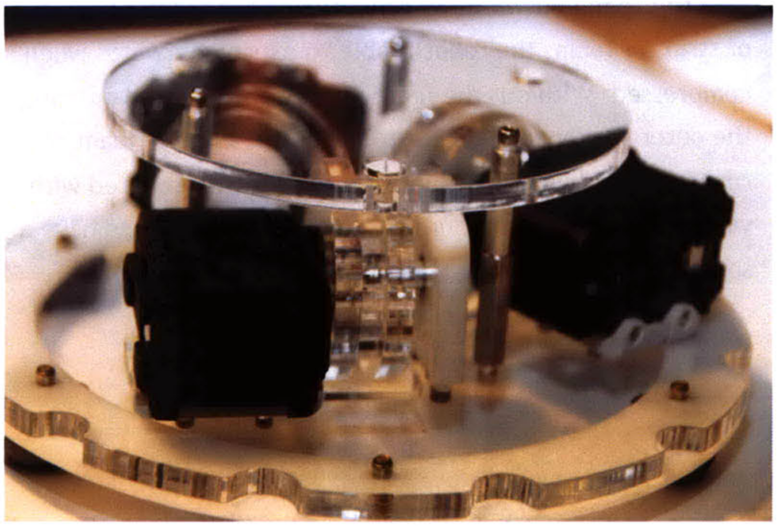
6.1 Design of Tofu - Expressive Robot One

Tofu is the first robot made during this project and was designed as a general platform for simple social interaction. The robot is not mobile and requires an external computer and power supply to operate. Robot characters to follow explore mobility, wireless control, and different types of expression.

The Tofu robot is the first and simplest of the robot prototypes made and requires an external computer and power source to operate.

Mechanical Design

The mechanical design of Tofu is by far the simplest of the robots presented in this section. Four servo motors provide the force needed to move the robot. Acrylic was used to construct the robots internal structure. In the base of the robot are three servo motors, which are configured as winches. Each winch is composed of a motor attached to a spool, which pulls a string towards the robot's base.



Three servo motors configured to be winches are symmetrically placed at the base of the robot to actuate the robots body.

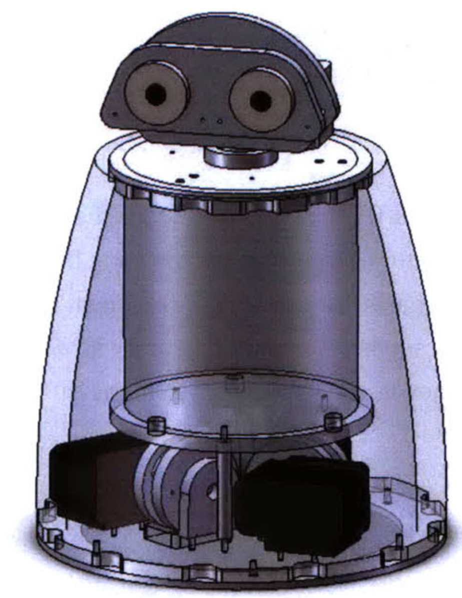
The core of the Tofu robot is composed of bedding foam or polyurethane foam. This core is sandwiched between the robot's top and base. By pulling the top down towards the base, the robot squashes up and down. By having three different winches in the robot's base, many different robot positions are made possible.

By actuating the servo driven winches in Tofu's base, many different poses are possible.

An additional motor is placed at the top of the robot to actuate the head in the pan axis. The external form of the head is made from Styrofoam and short black faux fur fabric. In the front of the head is a flat panel that holds the robot's OLED display eyes. Short black feathers are used as an aesthetic covering for the face of Tofu. Two large ostrich feathers are used for the robots ear like antennae.

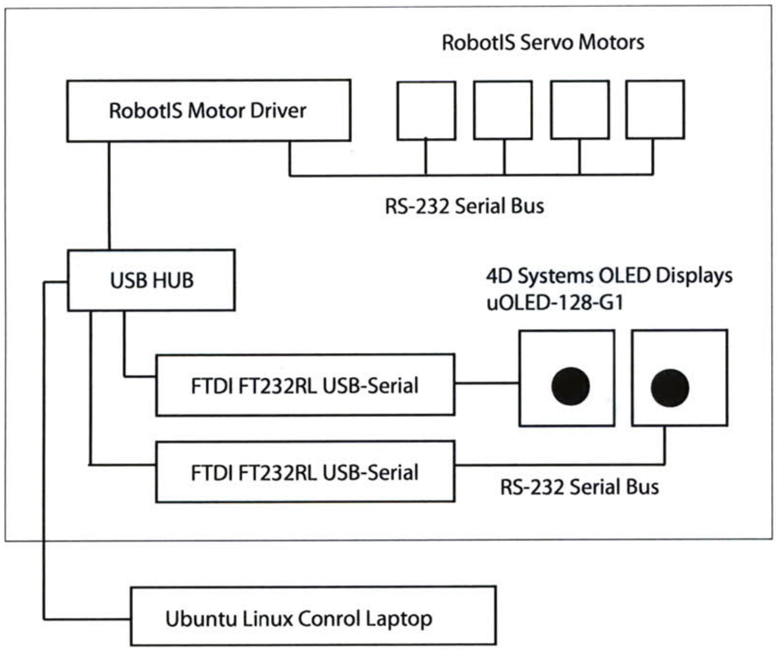
The most important innovation made with the Tofu robot is the method used for squash and stretch. The squash component is achieved using the winch based compression of bedding foam, described above. To achieve the illusion of stretch or expanding out when pushed down, the body of Tofu must be able to expand outward. By constructing the robot's body out of strips of foam, the robot is able to expand outwards when compressed. With out the feather boa covering used on Tofu, the outer shell would appear to be eleven strips of foam running vertically. When the strips of foam are covered with vertically attached feather boas, the robot appears to have a squashing and stretching body made of a uniform surface.

CAD Drawings of Tofu show the simplicity of the design when the fur covering are removed.



Electrical Engineering

Very little custom electrical engineering was required for Tofu. An external computer controls the robot through a USB interface. Two OLED displays manufactured by 4D Systems are used as the robot's eyes. Each display operates using RS-232 communication and connects to the control computer via USB to RS-232 converters made by FTDI. The four servo motors used also require a RS-232 interface. The USB to RS-232 interface board and servo motors used are both manufactured by Robotis. In addition to communication, power is provided to the system using an external DC power supply. An onboard linear power supply provides 5V of power to the OLED eyes.



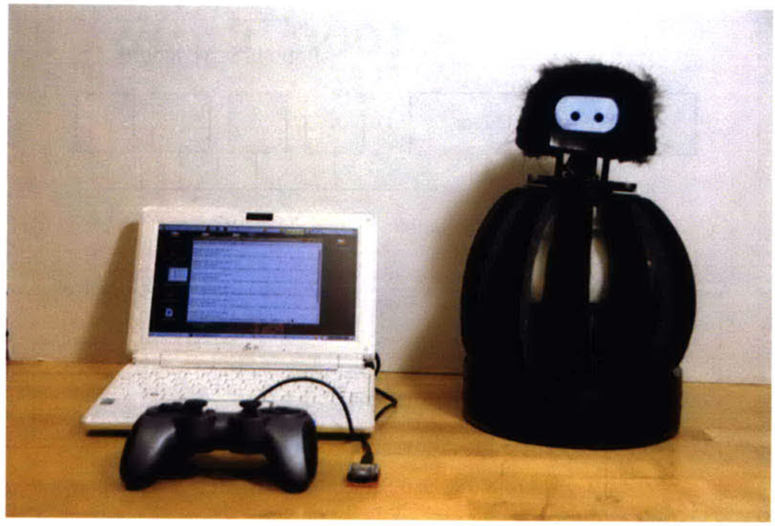
Block diagram of the electrical subsystems used for the Tofu Robot.

Software Engineering

The software used to operate Tofu is very simple in design. A python script running on a Ubuntu linux machine reads the state of a Gamepad controller and uses the input to drive the motor and eye states of the robot. Some of the controls are mapped directly to the robot's state, such as the Gamepad joystick and the position of the robot's eyes. Other behavior is more complex and is only triggered by the Gamepad. For instance, the "D" button has been mapped to a special dance Tofu does to which would be difficult or impossible to do with direct mappings.

6.2 Design of Mochi - Expressive Robot Two

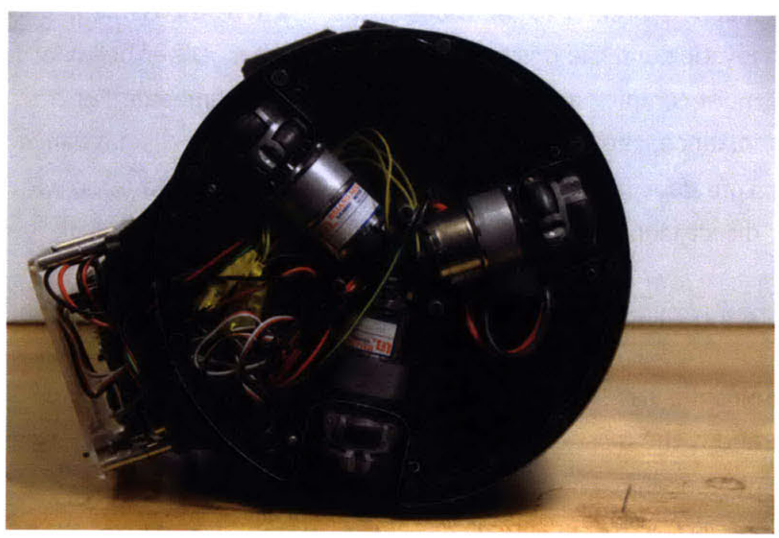
Mochi is the second expressive robot created in this project and is the most complex from an engineering standpoint. It was obvious that Tofu as a robot was doing something right and in many ways the design was stumbled upon. Mochi was designed to explore the use of wireless mobility and head articulation as added degrees of expressive freedom. Knowing that Mochi would be interacting with young children, the mechanical design used for Mochi is very robust.



Mochi is the second robot made in the series and by far the most complicated and robust.

Mechanical Engineering

The mechanical systems used for Mochi were designed with robustness in mind. Most of the components used on the robot are either 3d printed ABS plastic or laser cut delrin. Unlike Tofu, Mochi is able to move around using an omnidrive base. This is achieved by using special wheels (omniwheels), which are able to apply a force to the ground when spun about their axis, but move freely when moved in the direction of the axis.

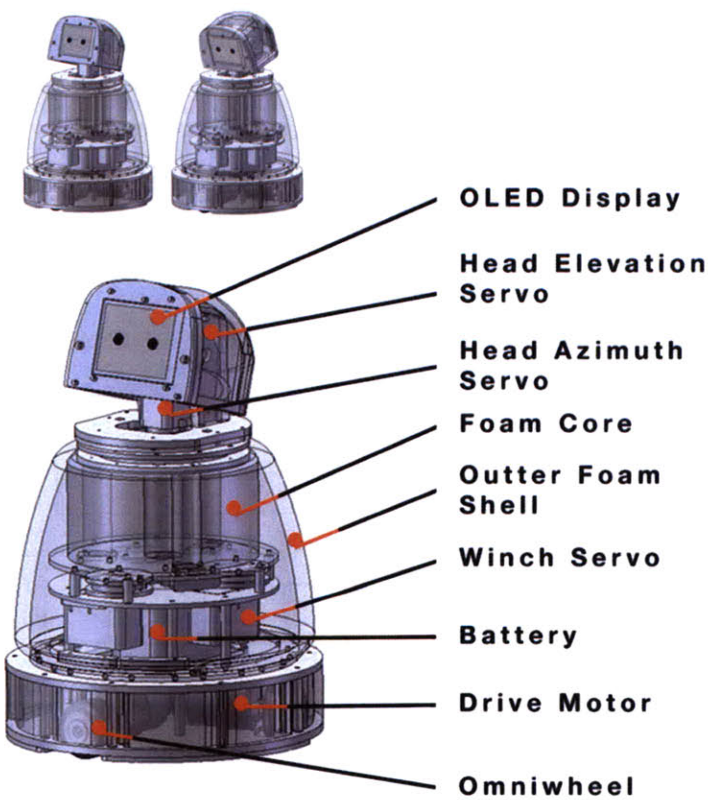


Instead of a traditional differential or "tank" style base, Mochi uses a complex omnidrive system that has the ability to translate and rotate at the same time.

By using three of such wheels, the base is able to translate and rotate simultaneously. Each axis is tangent to a single plane and 120 degrees from the other two. Three motors are used to drive the robot's three omniwheels. The base itself is made of Delrin and Acrylic.

Since Mochi is covered in Velcro, his aesthetics can be changed very easily.

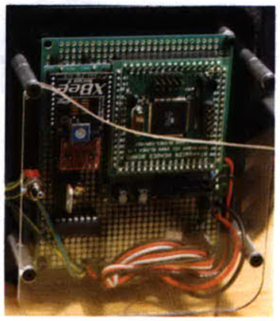
Like Tofu, Mochi has a body designed to squash and stretch. Three servo motors are configured as winches to compress the robot's foam body downward. The outer shell is also composed of strips of foam with Velcro attached to the outside surface. The intended purpose for the Velcro is to provide a means of reconfigurable aesthetics.



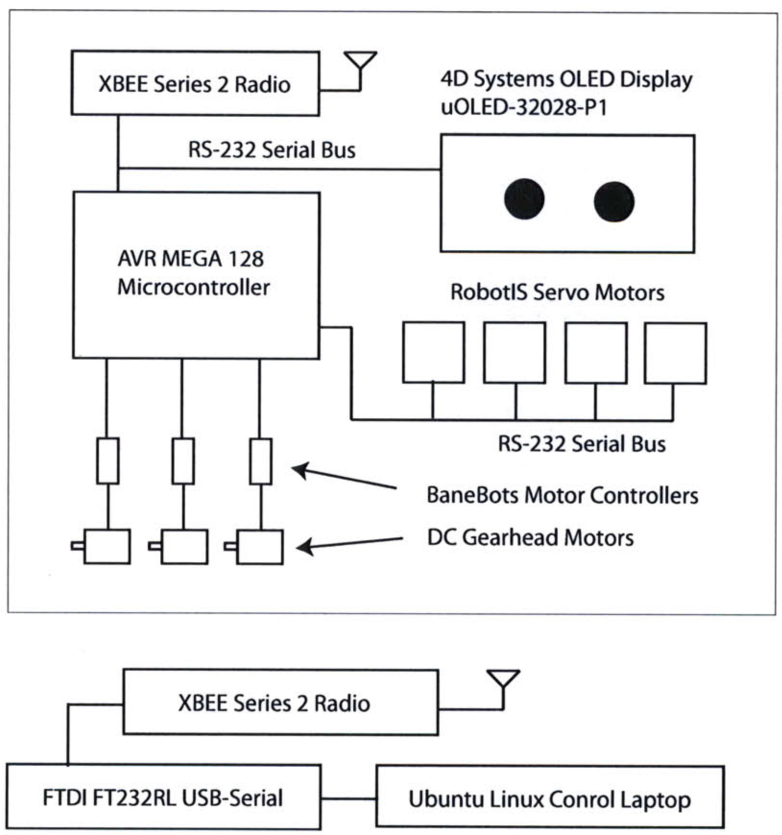
Since Mochi is wireless and mobile, a large number of components must be packed in it's little body.

Mochi's head is very robust in comparison to Tofu's which is made of Styrofoam. The internal structure of Mochi's head is made from delrin. An elevation and azimuth degree of freedom were put in Mochi's head to enable the robot to look up and down as well as left right. As with Tofu, Mochi uses an OLED display to convey eyes. Instead of using a display for each eye, Mochi uses one large display for both eyes. The Outer shell of the head was made using a Dimension 3D printer.

Electrical Engineering


Control electronics for the Mochi robot.

Since Mochi is wireless and mobile, the electrical systems on the robot must be able to digitally control every actuator used for mobility or expression through a wireless interface. To accomplish this, a small Atmel MEGA128 microcontroller was programmed to interface to a wireless data link and control the robot's outputs. Wireless data is sent through a set of 2.4 GHz XBee Radio links. This enables an RS-232 data stream to be sent to the microcontroller. The OLED eye display is controlled by a RS-232 data link by the Atmel microcontroller, as are the Robotis digital servo motors used to actuate Mochi's body. Three small DC drive motors are used to move the robot, which are controlled by open loop motor control, or without position feedback. To drive the three motors, a small commercial controller was used (BaneBots Motor Controller) to convert RC servo signal inputs into variable speed and direction motor



Block diagram of the electrical subsystems used for the Mochi Robot.

drive using PWM or Pulse Width Modulation and an H-bridge circuit.

Software Engineering

Like Tofu, Mochi is controlled through a Gamepad interface. Outputs generated by the gamepad are read by a small Linux Laptop. The python script generates behaviors for the robot based on the gamepad inputs. The gamepad joysticks are directly linked to the robots eye position and base velocity. Since Mochi has significantly more output options than Tofu, a single gamepad controller was difficult to use when controlling all of the features for Mochi. To help with the user interface bandwidth, different mappings were made for the gamepad, which could be selected by pressing a button. The desired position for Mochi was sent from the python script to the robot through a RS-232 serial stream as a packet of variables with a header and checksum represented in byte form.

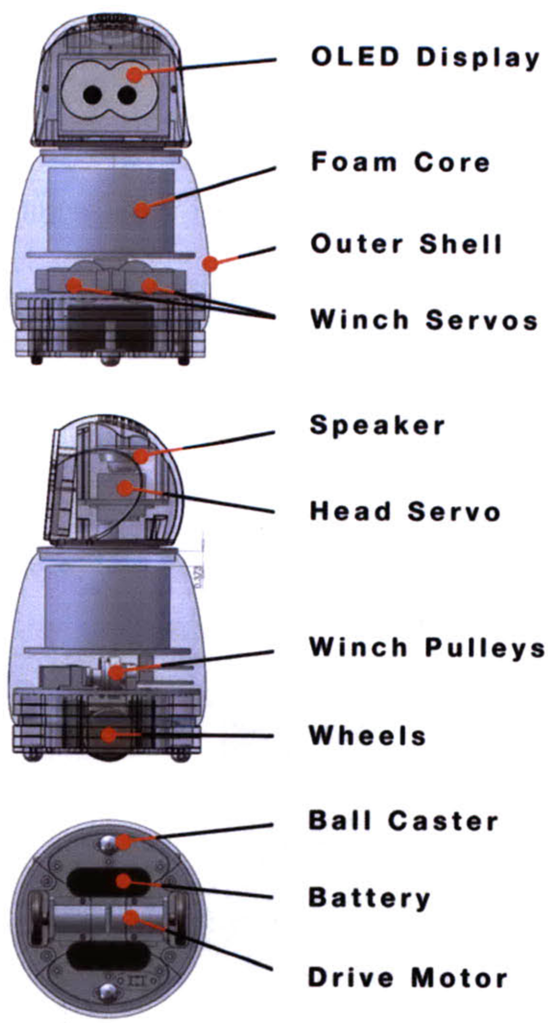
6.3 Design of Miso - Expressive Robot Three

The third robot in the design exploration can be thought of as an exploration into a specific robot form, which is a supplement to Tofu. Mochi was an exploration driven by a list of features, miso was made by navigating the design towards an emotion. The aesthetics are not reconfigurable, but fixed with the intent to resemble the offspring of Tofu. Although the appearance of Miso is very cute and small, a large number of components packed into the little robots body.

Mechanical Engineering

Although the appearance of Miso is very cute and small, a large number of components packed into the little robots body.

Like Mochi, Miso is designed as a wireless and mobile expressive robot. After finishing Mochi, I observed that the expressitivity of Mochi's omnidrive base did not justify the complexity required to construct it. For this reason, a more traditional differential or "take tread" style base was used to mobilize Miso. The general construction techniques used for Miso are very similar to those used in Mochi. The internal frame of Miso is also made of Delrin and custom fabricated 3D parts made of ABS plastic, such as the robots head shell. Miso's body core is made of compressible foam like Mochi and Tofu. A similar actuation technique was used to articulate Miso, where two RC servo motors are used as winches to compress the robots body. Since only two winches are used, as opposed to

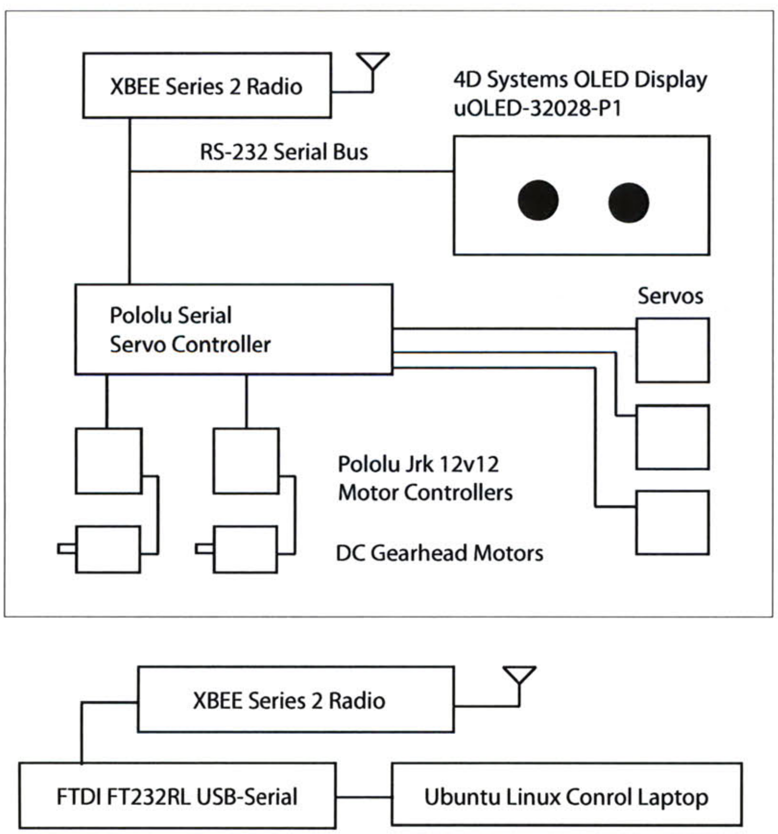


Simi-transparent CAD models of Miso show the large number of parts required to make the small robot, wireless, expressive and mobile.

three used in Tofu and Mochi, Miso can only lean left to right and quash down. An additional servo embedded in the robot's head allows the head to pan left and right.

Electrical Engineering

To simplify Miso, the robot was designed without any custom computation on the robot itself. Like Mochi, a wireless serial interface was used to send RS-232 data to the robot through use of a 2.4 GHz data link. Control electronics on the robot convert the RS-232 data in to the robots output. Actuation of the robot's body is enabled through the use of RC servo motors. The robot's base is controlled using the BaneBots Motor Controllers, which are driven by a servo control signal input. Since all the actuators on the robot are either a servo or can be controlled by a servo interface, a single servo controller was used to drive the robot's actuators. Input to the servo controller, manufactured by Pololu, is RS-232, enabling the servo to be controlled directly by the wireless data stream. In addition to the servo controller, the large OLED display used to



Block diagram of the electrical subsystems used for the Miso Robot.

generate Miso's eyes, was also listening to the RS-232 serial stream for data, allowing the entire robot to be controlled by the wireless data link.

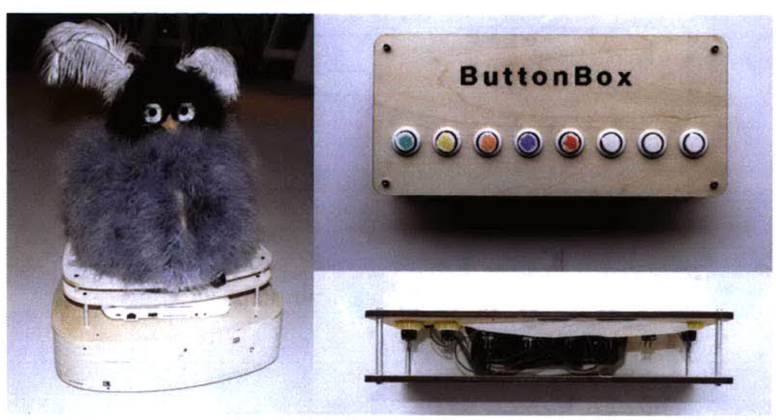
Software Engineering

The control method used for Miso is very similar the Miso. The signals from a gamepad interface are read by a python script running on a small linux laptop. These signals are used to generate behaviors for Miso by mapping the gamepad's inputs to the robot's face screen and actuators.

6.4 Design of Tofu Base

For the TofuDraw system, it was desirable to have a robot as expressive as Tofu and also Mobile. To accomplish this, a small base was made for tofu to drive around in. A small laptop rests on the base and is used to control Tofu and the base. For the TofuDraw study, two people are used to control the mobile Tofu and base robot. One person navigates the robots base and the other controls the expression of Tofu. To achieve this, a custom controller was made to allow a operator to easily change the mode of Tofu's expressions. This controller is referred to simply as the "ButtonBox". In addition to the buttonBox, a wireless gamepad is used as an input.

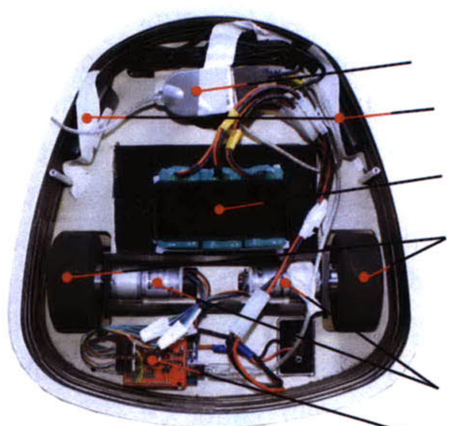
A wireless gamepad allows operators to easily control the Tofu Base from a distance.



The Tofu Base is a simple way of making the Tofu robot mobile. Using the ButtonBox, operators can wirelessly control the behavior of Tofu while on the base.

Mechanical Engineering

Both the Tofu Base and ButtonBox are constructed out of baltic birch plywood which has been laser cut and assembled. A combination of glue and mechanical fasteners have been used construct the assemblies. The Tofu Base uses a differential drive mechanism for mobility. Two 24V DC gearhead motors are used to move the robot, and are fixed to the base using a custom delrin bracket. Each motor propels the robot using a three inch foam wheel made for RC plane use. A small furniture caster on the back of the base allows the robot to move around freely. All power and communication are contained on the robot's base. Batteries are stored low and near the robots center to keep the robot stable and with a low moment of inertia.



Inside the base, two DC Gearhead motors provide power to the wheels, which move the base around.

Electrical Engineering

The ButtonBox in function is used to relay button states wirelessly to the mobile Tofu Base platform. Instead of doing this using custom electronics, the ButtonBox simply uses the electronics from a wireless gamepad controller to relay button states to the computer. To do this, a wireless gamepad was disassembled and removed of all the input buttons. The arcade buttons from the ButtonBox were then soldered into the wireless gamepad control electronics.

An Arduino and Motor shield are used to control the robot's two drive motors.

The Tofu Base platform is controlled directly by the laptop, which rides on top of the robot. To provide a simple way of controlling the robot, an Arduino board was installed into the Tofu Base and used to drive the motors that drive the base. To drive the motors, a "motor shield" made by Sparkfun was used. Control signals are sent from the Arduino to the motor shield to control the rate and direction of the motors. Each motor has a small hall effect quadrature encoder on the motor to sense the position and rate of the motor. To power the Tofu Base, three 7.2V NiMH batteries are connected in series to approximate the 24V power needed to fully use the drive motors.

Software Engineering

Software used to control the Tofu Base was written to run on the Arduino within the base and on the small laptop that rides on top of the base. Python code used to control the Tofu Base is the same as that used for Tofu, with the addition of code for controlling the base motors target wheel velocities. The Arduino code has several tasks. The first is receiving data from the laptop by parsing a packet of data sent over the built in USB communication on the Arduino. Target wheel velocities are sent to the robot and used to control the speed of the motors. The actual wheel velocities are measured by counting motor encoder ticks per unit time. The voltage sent to the motors is determined by using a PID control system. In this case, only PD control was used to maintain the target velocity. Variable control over the voltage sent to the motor is achieved by PWM and an H-bridge circuit on the motor shield.

6.5 Design of the Digital Painting Interface

The digital painting interface is designed as a means to control the TofuDraw system. Since the Tofu robot and the Base it uses for mobility are both puppeteered by an operator, there is no need for the painting interface and the robot to be interfaced in any way. Although the Tofu robot and the painting interface are used together during interactions, the two systems have been technically developed as isolated systems.

The purpose of the digital painting interface is to provide a method for children to paint on the ground as a digital medium using affordances similar to physically painting. To accomplish this, a motion tracking system has been used to track the exact 3d location of a digital paint brush. If the trigger of the digital paintbrush is pressed, the position of the brush can be used to control where digital "paint" is projected.

The Digital Palette

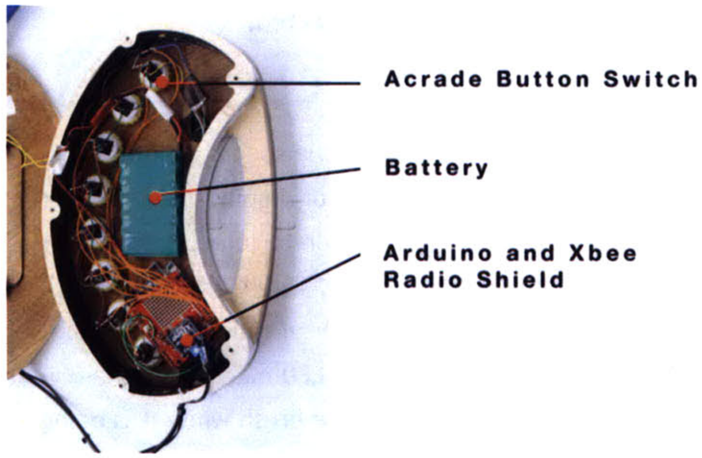
To enable children to digitally paint, a special paintbrush and palette have been created. Instead of dipping the brush in paint, a set of buttons allows children to select a different color, or functionality such as erase. The paintbrush itself has a button which engages the painting or erasing, if that is the selected functionality. Small active LED markers on the digital brush are used to track the tip of the brush while it is being used. The small pack on the back of the digital palette is used to drive the LED markers used for tracking the digital paintbrush.

Once a color is selected on the palette, children can paint projected light using the digital brush.

Within the digital palette are eight switches. An Arduino reads the button states and knows when any of the buttons are pressed. The Arduino sends data to the computer running the painting software for generating interactions. Data is sent over an RS-232 data stream using a pair of 2.4 GHz XBee radio links.

The tip of the digital paintbrush has four LED markers, which are tracked by an eight camera PhaseSpace motion capture system. Each marker emits a light pattern in the IR frequency range. This marker is tracked by the eight cameras to determine the markers position in cartesian space.

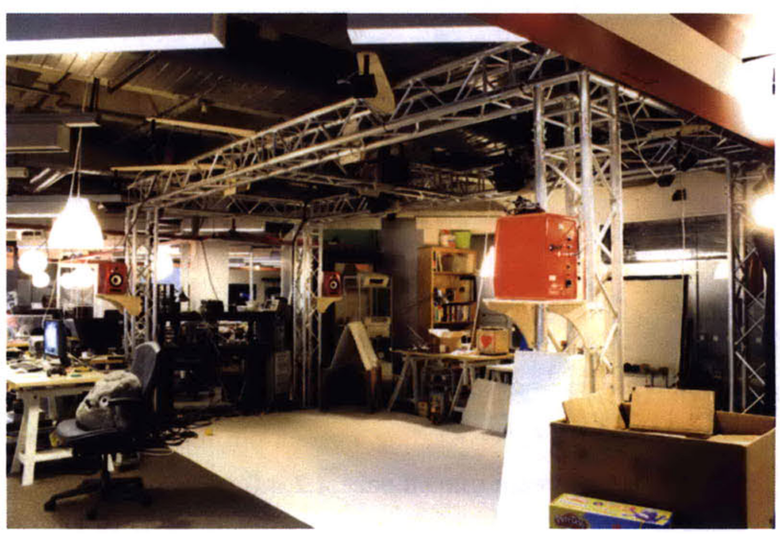
Inside the Digital Palette button states are read and sent to a control computer wirelessly.



Projectors attached to the truss structure are used to project digital paint onto the ground.

The PhaseSpace system sends the location of the tracked points over a custom network interface. A small program written in Java accepts packets using this interface to determine the position of the digital paintbrush. Knowing the position of the paintbrush and the button states from the digital palette, a program written with the Processing java library paints onto a digital projection.

A large Aluminum truss structure holds the projector and cameras used to track objects in the space.



7 Studies with Children

In this section, two studies are presented that were performed to gain insight into how children use and could use expressive robotic characters as an element of fantasy play. The first study presented uses the Mochi robot to act out a story which is being collaboratively generated by a group of preschool aged children. In the second study, small groups of children in the three to eight-year-old age range were given interfaces that enabled them to choreograph the behavior of an expressive robotic character.

7.1 Pilot Study with Preschool Class

Before developing the current TofuDraw system with interfaces to enable choreographing robotic behavior, it was desirable to observe how children respond to expressive robotic characters as a component of dramatic play. To do accomplish this, the Mochi robot was taken to a preschool class to engage in a story generation activity with a group of preschool age children. Fifteen children, boys and girls around the age of five participated. The children, who were all in the same class had previously studied the basics of storytelling and were familiar with general elements of plot, setting, character, antagonist and protagonist.

The Mochi robot was taken to a preschool class to engage in a story generation activity with a group of preschool age children.

Specific Study Goals

The goal of introducing the Mochi robot to a preschool age group of children in a storytelling context was to observe how a puppeteered robot could be incorporated into a storytelling activity. More specifically, how children's stories could be influenced by the behavior of the robot. I also observed how engaging the robot augmented experience was to the children and how children incorporate physical props as characters and story elements into the storytelling activity.

Study Format

To test the interaction patterns children have when engaging in a storytelling activity that incorporates a puppeteering robotic character, I deigned an activity that allows each child to help "dress" the robot and also get a chance to become part of a story involving the robot. When dressing the robot, each child was given the opportunity to add one aesthetic element to the robot's body using Velcro. During the storytelling activity each child would add to an emerging story. Although the story was created verbally. Each child, when it was their turn was encouraged to add characters or props, which were available to the group.

Introducing and Dressing Mochi

Before starting the story generation activity, Mochi was introduced to the group of children who sat in a circle with their teacher. The group of children had recently performed an exercise with story generation a couple weeks earlier, where each child added a story element on their turn. "Today, we are going to play the same game, but with a new friend whose name is Mochi," explained the teacher. At this point, Mochi was introduced to the the circle by driving into the center and looking around. I served as the controller of Mochi and was introduced as such to the group. After demonstrating some of

Children "dress" the Mochi robot using reconfigurable Velcro based aesthetic coverings.

Mochi's movement and expression capabilities, the class was asked if they could help Mochi with something before we got started. At this point a large number of Mochi's reconfigurable aesthetic coverings were put on the floor. Guided by the teachers instruction, each child picked an element and placed it on the robot.

Transcription from Dressing Activity

[Teacher] "Boys and girls, we're each going to add just one thing, and so, we will just have to see what the group does"

[Teacher] "I'm noticing that there are little pieces of Velro", "So, when you take pieces of this (fluffy aesthetic), you want to put the little pieces of velcro, and put them on his body, so it sticks, ok?"

[Teacher] "Maybe we will do the body first, and save the head things for later"

Children were asked to "dress Mochi using velcro based reconfigurable aesthetics"

[Teacher] "So Ryan, can you add one piece to Mochi?" (Ryan, places a teal strip of feathers on Mochi)

[Teacher] "So Ryan, can you add one piece to Mochi?"

[Teacher] "When he's(Mochi) all done, he will be decorated by all of us"

[Teacher] "Abbey, why don't you add a piece now. Ryan, scoot back into place." (Abbey looks through a few options of feather strips, and then finds a white collar piece.) "Ah" she says, as she reaches to pick it up and place the white collar on the robot)

[Teacher] "Anna, can you add a piece?" (Anna giggles as she reaches for a strip of pink feathers without hesitation and puts the strip on Mochi. Anna is also wearing pink.)

[Teacher] "Zoe, will you add a piece?" (Zoe also goes for the strip of pink feathers with out hesitation, and places it on Mochi.)

[Teacher] "Ariana, will you add a piece? You may need to lift up the white part to attach it; you need to attach it under the white part. It needs to attach to the black part." (Ariana, reaches straight for the pink strip of feathers and tries to attach it to Mochi's white collar. The teacher then helps lift up the white collar to expose Mochi's Velcro body.)

[Teacher] "Aliza" (Aliza successfully attaches a strip of teal feathers.)

[Teacher] "Alana, - it's starting to look very beautiful. I wonder if there is going to be a pattern or not?" (Alana places

By puppeteering Mochi curing the dressing exercise, participants became more engaged in the activity.

a black strip of feathers on the robot. "Oh!" says the teacher, Children laugh as Mochi turns his head towards the new strip of feathers places on him.)

[Teacher] "Ok Daniel, do you want to add a piece? I'm pretty sure he doesn't bite (referring to Mochi)" (Daniel is a little hesitant, but add's a black feather strip to Mochi.)

[Teacher] "Ok Alexander, can you add a piece? (Mochi is getting full of feather strips of different colors)" (The teacher then describes to the children which remaining regions on Mochi can be used for decorating.) "I don't thing feathers can be put here." While pointing to Mochi's head. Alex puts a large green collar over Mochi's head.

[Teacher] "What do you think Rohan?" (Rohan finds a place to put a strip of blue feather with the teachers help. Mochi is getting full of feather strips.)

[Teacher] "Jenna?" (Jenna, mentions that she wants pink.) "Ok, I think there is lots pink" responds the teacher.

[Teacher] "Ok James, can you look over here" (Pointing to a small space to put a strip of feathers.) "Ok, Hana, there is a good spot over here" (Picking up the pace while the last of the children finish putting a decoration on Mochi.) "Ok, Ben" (Ben puts on a strip of feathers.) "You need to put it on the black part, there you go"

[Teacher] "Ok, why don't we use these during the story" (referring to the head bands for Mochi. "Ryan, do you want to put one of the head pieces onto Mochi to get us started?" Ryan goes for the headband with two large pink feather on it, and places it proudly on Mochi. The children and the adults in the room both laugh at how silly Mochi looks.)

Story Generation with Mochi

The roll of the puppeteer was presented to the children who could also see the puppeteer during the exercise.

Once the aesthetics of Mochi were customized, a brief description of the storytelling exercise was given to the children. The teacher informed the children that they would go around the circle, at which point each child would add an element to the emerging story. The main character Mochi was introduced as well as other potential characters including a stuffed crocodile and caterpillar, who could be included in the story in the form of friend or possibly foe. A small cardboard house was also introduced as the house of Mochi. As the children told the story of Mochi, the robot would act out the story through a puppeteer's control. The roll of the puppeteer was presented to the children who could also see the puppeteer during the exercise.

Fifteen preschool age children engaged in a storytelling activity with an expressive robot character.

Transcription from Storytelling Activity

[Teacher] "So, remember boys and girls when we were telling our own stories, we were using; we thought of a character." (The boys and girls sit in a circle with Mochi in the center.)

[Teacher] "We have the main character, and that's Mochi; and just so you know, this could be another character, a friend or foe of Mochi's in the story." (Holding up a toy stuffed caterpillar.)"This can be another character in the story, friend of maybe not friend, I don't know. Maybe you decide." (While holding up a stuffed alligator.) "So we are going to make up a story, but these can be some of the characters in the story, ok"

[Teacher] "We often have a problem that we need to solve. We need to decide wether Mochi has a problem, or he is going on an adventure. And these characters, we need to decided if they are nice, friends, or whether they are not so nice"

[Teacher] "So remember when we talked about setting," (Mochi drives into the house shaped box at the side of the circle.) "Now that can be a castle, or a cave, it can be whatever we want it to be. For each part of the story we are going to tell, what you say will be written down and today or tomorrow, you will draw a picture of what you write down." (showing a blank sheet of paper.)

The house shaped box is introduced as a story element that can become anything the children want.

[Teacher] "Ryan do you want to start the story - once upon a time?"

[Ryan] "Once upon a time,... Mochi was in his house."

[Teacher] "Ok there he is, Mochi is in his house." "And Abbey, does Mochi need to leave his house for any reason? Or what happens next in the story? Doe he need something? Whats the problem that causes Mochi to go out?"

Since Mochi did not have any friends, he went out of his house to find some.

[Abbey] "Mochi needed to have friends and he didn't"

[Teacher] "Mochi didn't have friends! So Anna, Mochi doesn't have friends what do you think?" - repositioning stuffed characters on the ground. Anna grabs the stuffed caterpillar and throws it over to a position near Mochi. "Can you tell us? Who is that? Does Mochi come out into the world and come out of his house?"

[Anna] "He comes out of the house"

[Teacher] "He comes out of the house. And who does he meet?"

[Anna] "His name is Mr. Catapiller." Mochi moves out of his house and moves across the floor. Children and adults laugh.

[Teacher] "So Mochi meets Mr. Catapiller. And what does Mochi Say to Mr. Catapiller?"

[Anna] "Um Hi.."

[Teacher] "Why don't you pass Mr. Catapiller to Zoe. Now Zoe, what does Mr. Catapiller say to Mochi?

[Zoe] "How are you doing" (softly)

[Teacher] "How are you doing? And does Mr. Catapiller need help with anything?"

[Zoe] "Yeah"

[Teacher] "What does he need help with?"

[Zoe] "finding food"

[Teacher] "He need help finding food! Does Mr. Caterpillar ask Mochi to help him find food? (she nods yes.) "Can you ask for him?"

[Zoe] "Can you help me find food?" While holding Mr. Caterpillar. Mochi nods it a yes motion.

Mochi and Mr. Caterpillar go to a restaurant.

[Teacher] "Ok, why don't you pass Mr. Caterpillar to Ariana. Ariana, what do you think happens next? Where are the caterpillar and Mochi going to look for food."

[Ariana] "Mr Caterpillar and Mochi say lets go to a restaurant." (Mochi shakes his head yes.)

[Teacher] trying not to laugh, "A restaurant. Aliza, Aliza what do you think? Also, one of these guys could work in the restaurant... So Aliza, what do they do next?"

[Aliza] "They got in the car"

[Teacher] "they got in the car, who drove?"

[Aliza] "Caterpillar"

[Teacher] "And where did they go?"

[Aliza] "the restaurant"

[Teacher] "What restaurants do caterpillars and.... funny little creatures go?"

[Aliza] "I don't know..."

[Teacher] "But you can make it up, this is your story." Pause - "Ok why don't you pass it (caterpillar) to Alana, maybe Alana can figure out what happens when they get to the restaurant."

[Alana] "They have tofu."

[Teacher] "They have tofu! (Laughing breaks out in the room.) So they have Tofu at the restaurant? Does anything else happen at the restaurant? No? Ok, why don't you pass it (Mr. Catapiller) to Daniel, and Daniel, is there anything else you would like to add? Is there anyone else at the restaurant? Another character you would like to add?"

[Daniel] "They went home." (Mochi drives back into his home. Daniel walks Mr. Catapiller over to Mochi's house.)

[Teacher] "Ok Sterling, what happens next to Mochi in our story?"

[Sterling] "I want that guy." (pointing to one of the other plush characters.)

[Teacher] "You want that guy? Ok, Sterling, can you tell me what happen next in the story? And sterling can you tell me who that character is?"

[Sterling] "Mr. Blunder Shlipter Shlapter Shlap"

[Teacher] "Oh, I don't even know how to spell that. Can you say that again?"

[Sterling] "Mr. - Blunder - Shlipter - Shlapter - Shlap"

[Teacher] "Ok, so Mr. Blunder Shlipter Shlapter Shlap, (Mr. B, for short) did he come to the house?"

[Sterling] "Yeah!"

[Teacher] "Ok can you take him over to there house? You need to put him on your hand." (Mr. B is a hand puppet) (Sterling puts on Mr. B and moves over to the house, where Mochi and Mr Caterpillar are.) "And what did he do? Did he Knock on the door?"

[Sterling] "He breaks in"

[Teacher] "He breaks in, is he a bad guy? So why does he break into the house?"

[Sterling] "Because he, ah, he is too excited and breaks in."

[Teacher] "And what does Mr. Mochi do when Mr. B breaks into the house? Is he scared? How does Mochi feel?"

[Sterling] "He breaks out of the house"

[Teacher] "Mr Mochi breaks out of the house because he is so nervous?" (Alex nods yes,) "Here he Comes!" (Mochi comes busting out of the house to the center of the circle and spins around - children respond by laughing and leaning back. Mochi moves to another place in the circle and spins around - children laugh more and lean back.) "Alexander, what happens next?"

Mochi runs out of his house to escape from Mr. B. Mochi then runs around in excitment, and starts to dance because he is so happy.

[Alexander] "He dances!"

[Teacher] "He dances, why does he dance?"

[Alexander] "Because he is so happy"

[Teacher] "Happy because he is away from Mr. Blunder ... whatever."

[Alexandria] "Yeah!"

[Teacher] "Alexandria, does Mr. Caterpillar do anything in all this?"

[Alexandria] "Mr. Caterpillar, runs away and beside Mochi."

[Teacher] "So he runs beside and the two friends are together again?" (Alexandria picks up Mr. Caterpillar and puts him next to Mochi). "Ben, now remember there is still a crocodile, and an airplane - if you want to add any of those." (Ben grabs the plush crocodile animal.) "So who comes along?"

[Ben] "The crocodile comes along and tries to eat Mochi...." (Ben motions the crocodile towards Mochi while moving the crocodiles mouth open and closed. Mochi runs around the circle in fear of the crocodile.)

[Teacher] "And Rohan, what happens next?"

[Rohan] "The airplane comes along, and, and, picks up the caterpillar and.. Mochi; and they go in the airplane together to get away from the crocodile." Rohan sets the stuffed airplane down to Mochi and Mr. caterpillar

[Teacher] "Ok, Jenna, what happens next?"

[Jenna] "And then, they, they.... find the caterpillars house."

[Teacher] "Oh!, they find Mr. Caterpillars house?"

[Jenna] "And he becomes the roommate."

[Teacher] "And he becomes roommates with Mr. Caterpillar? Ok, here we go, they come together and become roommates at the Caterpillar's house. And Zane, what happens next when they are at the Caterpillars house? Come tell us!"

[Zane] "They put on a disguise"

[Teacher] "They put on a disguise! Hana can you come and put a disguise on Mochi and Mr. Catapiller? Hana puts one of Mochi's headbands on Mr. Catapiller. Hana can you tell me what they do in their disguises? What do they do when they are all disguised?"

[Hana] "When they are all disguised, they, they, go and see if the crocodile is scared of them."

[Teacher] "Ok Kyle, you are going to go next because you haven't had a turn yet" Carl comes to the session late and sits in the circle with the rest of the children. "We are making up a story with Mochi" (pointing to Mochi) "And mochi has become friends with Mr. Caterpillar. And they were scared away by the crocodile. Now they put on a disguise and they are going out to see if Mr. Crocodile is scared." "Now Carl, I know you just came in, but do you want to add something to the story? Do you think the crocodile will be scared of Mr. Caterpillar and Mochi?"

[Carl] "I don't think so.."

[Teacher] "So the Crocodile isn't scared?"

[Hana] "Why isn't he scared!"

[Teacher] "You know what, but Hana, it's Carl's turn. Carl, can you make a scary face at Mochi?" Teacher hands the crocodile to Carl, who wears the Crocodile as a puppet and motions it towards Mochi. Mochi, runs around in fear when the crocodile is reintroduced."

[Teacher] "Ok lets give the Crocodile to Ryan. So Ryan, what happens next."

[Ryan] "The Crocodile eats his friend."

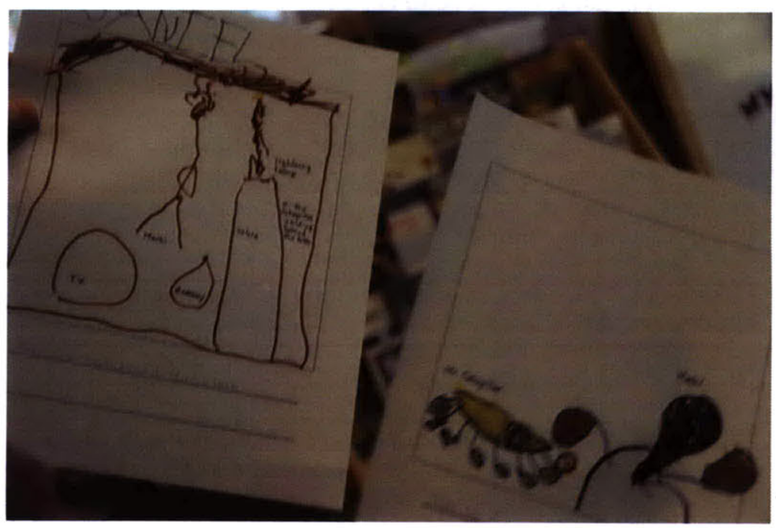
[Teacher] "He eats his friend? Which friend, the Caterpillar? Ryan nods yes and motions the crocodile into the Caterpillar as if eating the Caterpillar. oh no" - commotion.

Summary of the rest of the story:
Abbey - Mochi ran to his house to get away from the crocodile.
Carl - Mochi ran so far into his house the crocodile couldn't keep up.
Anna - Mr. B scares Mochi out of his house.
Zoe - Mochi washes off.
Ariana - The Crocodile scared them.

Aliza - Mochi got on the airplane to get away.
Alana - The Crocodile bit the airplane and brought it back down.
Daniel - The Crocodile bit it harder and the airplane broke in half. The one piece of airplane that kept flying had Mochi on it, and he was ok.
Sterling - The Crocodile wanted to hear Mochi so he put on antenna.
Alexandria - That disguise didn't work.
Ben - The crocodile tried to bite off Mochi's head, but he fell back.
Rohan - His antenna fell off.
Jenna - The crocodile is getting tired from chasing Mochi, and he takes a nap.
Zane - And then he gets on an airplane and flys away.
Hanna - The Crocodile burped up Capiller and he went all the way back to Mochi. Then they went and had dinner together. And then the Crocodile went on a vacation to the beach.

Drawing Mochi's Experience

During the story generation exercise, an adult volunteer recorded each child's addition to the story generation activity. After the activity was complete, each child's addition was printed at he bottom of a blank page to sketch on. Each child was then given the page and asked to draw what happened to Mochi during his adventure to help children reflect on the storytelling experience.



Each child was invited to reflect on the learning storytelling experience by drawing their segment of the collaborative story.

Refections on the Dressing Activity

To allow each child to participate in the dressing of the robot in a small time frame, a single chance was given to each child to add an aesthetic element to the robot. As a result, there did not seem to be a unified vision for the robots appearance, which ended up containing almost every color of fur available. Of interest would be doing a similar exercise where a discussion would take place about what the robot should look like before dressing the robot. Another interesting option would be to have small groups of children dress the robot as a team; where the group could iterate through different dressing configurations and converge on an appearance through collaboration. Once shown how to add an element to the robot using the Velcro pieces, the process seemed intuitive to the entire group.

Refections on the Story Generation Activity

The story generation exercise in addition to the dressing exercise lasted for approximately 50 minutes and kept the children highly engaged according to the teacher. The act of the robot moving in space added a surprisingly small amount of diversion to the exercise and mainly functioned in a way that kept the children engaged in the activity. Physical props were found to be a way to incorporate new story elements through questions like "remember we have an airplane and a crocodile." In many cases the physical prop being used currently in the story became a token passed around the circle, serving as a marker of each child's turn to add to the story.

The roll of the puppeteer was presented to the children who could also see the puppeteer during the exercise.

The elements of story added by the children ranged in complexity. Some additions provided by the children included general story elements, such as two characters becoming friends or going to a restaurant. More complex additions would take into consideration the intent of a character such as the crocodile wanting to sneak up on another character and dressing in disguise to do so. The robot was assumed to take on a character which could do things such as: be friends with a caterpillar, go to a restaurant, be roommates with its friend and be antagonized by a crocodile. Boys in the group in general were more prone to add elements of conflict and adventure to the story being told. The free form format of the storytelling exercise enabled a very creative story to emerge. By bringing the group up to the current point in the story with small summaries from the instructor, children were better able to add to a more cohesive story arc. Some unresolved story elements did form such as the introduction of a character that was forgotten in the middle of the story and not revisited. Resolution was brought to the story at the very end by having the antagonist burp up one of the main characters.

Although the story generation activity was only intended to obtain very general reactions children have to expressive robotic characters, the experience suggested that children found Mochi the robot to be engaging and had no problem incorporating the character into elaborate fictional stories. In many cases, the action of the robot in response to the story being told caused excitement and laughter in the classroom. Through the action of gesturing with the physical props, children commonly became part of the story by acting out their story element. Knowledge of the robot being controlled by a person in the room did not seem to affect the engagement children had in the activity or provide a distraction to the story being generated.

7.2 TofuDraw Study - Overview

To test the interfaces created for choreographing expressive robot behavior, I performed four studies with small groups of children. Each group included two individuals, who ranged in age from three to eight years old. Each of the four groups were introduced to the different choreographing interfaces created for the Tofu robot and mobile Base.

Study Motivation Format

In the storytelling with a preschool class study, the goal was to see how children could incorporate a robotic character into a storytelling activity when the robot is being puppeteered by an external controller. The TofuDraw study was created to see how different interfaces can be used to control robotic characters. The robotic character was introduced among other non robotic characters: teddy bear, gray furry stuffed creature and a small plastic robot toy. Children were introduced to the other characters to enable the children to incorporate the props into interactions with the robot. Through these interactions, we hope to gain insight into how children use the interfaces as a means to choreograph robot behavior. Specific items being looked at in the study include:

- Children's engagement with the interfaces when participating in an activity with an expressive robotic character.
- Children's ability to use the interface and understand the intended affordances of the interface.
- Children's perception of the robots autonomy in relation to their input when using the different interfaces.

Description of Interfaces

Three interfaces were introduced to the children during this study, which include: Digital Painting interface, GamePad, and ButtonBox. A detailed description of each interfaces functionality can be found in previous sections on design principles and hardware implementation. The basic functionality of the different interfaces are as follows:

Digital Painting Interface - Consists of a palette and brush use respectively to choose a color and paint with the color using a digital projection. Paintings made with the interface control the expressive robots behavior, through a following routine where the robot follows a line after it has been drawn. The color of the line dictates the emotion of the character. The act of painting provides realtime feedback; but the robot's behavior is not realtime but rather a turn taking between the child painting and the robot acting.

ButtonBox - Using the ButtonBox controller, children can remotely control one of six different expressions of the robot by pressing a button that correlates to each of the robot's expressions. This interface offers realtime control over the robots expressive behavior.

Gamepad Controller - Using the gamepad controller children are able to control the physical motion of the Tofu robot by using a joystick interface on the controller. This interface also provides realtime control of the robot's expression, but through motion.

Study Participants

The TofuDraw study consisted of four groups of participants. Each group of participant included two children who are also siblings. This pairing was chosen to select children who were familiar with each other and could collaborate when learn the behavior of the TofuDraw interfaces. The four groups of children were as follows:

Group 1: Two brothers, ages four and six.
Group 2: Two sisters, ages three and six.
Group 3: Brother, age-six and Sister, age eight
Group 4: Brother, age-six and Sister, age eight

Study format - Introducing Tofu

Once the group of children were introduced to the environment, the Tofu robot sitting on the mobility base would be introduced. Typically Tofu would be brought out after the group had been asked if they "would like to meet a friend of mine named Tofu." At this point Tofu would be set in front of the children alongside the other stuffed animal characters. Tofu would then remain stationary except for movement in the eyes, controlled by an operator from a distance using the gamepad interface.

Study format - Introducing Digital Paint

After the group had spent some time observing Tofu, they were asked if they would like to "play with Tofu." At this point the digital painting interface was introduced as a way to interact with Tofu. The digital painting interface was described as a special way to paint on the ground with light that Tofu could see. Without demonstrating the painting interface, the Digital Paintbrush would be given to one of the children in the group. They would then be verbally guided through the process verbally of pressing the button on the brush to paint on the ground.

Study format - First Steps with Tofu

After interacting with the Digital Painting interface, the group of children would be asked to help Tofu find his way back to his home. A large cardboard box with a roof positioned off to the side would be introduced as Tofu's home, which he is trying to find. On the other side of the play area, Tofu would be positioned and described as trying to find his home. To encourage the children to use the painting interface to control the robot, it would be mentioned that Tofu likes the color green. Once the child painted the color green on the ground Tofu would be controlled to move towards and then over the green spot. Once over the green spot, Tofu would do the "Stevie dance" corresponding to the green color. Following this demonstration, each group tested was able to draw a line to Tofu's home which completed the task of helping Tofu find his home.

Study format - Next Steps with Tofu

After the basic functionality was introduced to the group of participants, they where encouraged to explore the different capabilities possible with Tofu and the painting interface. Once they had explored different painting possibilities, the group would be asked if they would like to see another way to control the Tofu. At this point the ButtonBox and Joystick interface would be introduced as means of controlling Tofu. First the ButtonBox would be shown to the participants and demonstrated by pushing one of the buttons to activate a behavior in Tofu. The Gamepad controller would then be introduced as a way to control Tofu's mobility. Likewise the Gamepad was first demonstrated and then handed over for use.

7.3 TofuDraw Study - Interaction Case Study

The following section is a transcript of the study when introducing the Tofu robot and the digital painting interface to study group one, consisting of two brothers. The younger

Each group of children were introduced to the Digital Painting interface.

brother (age 4) is abbreviated in the transcript as B1 and the older brother (age 6) abbreviated as B2.

[Instructor] "Do you want to meet a friend of mine?"

[B2] "Ok!"

[Instructor] "You have to sit down first. He's kind of shy."

[B2] "Who is? is it ah, is it ah?"

[B1] "R2?"

[B2] "Is it that birdie bird guy?"

[B2] "ooh the birdie bird, I like him, he's fun."

[Instructor] "He's been sleeping so I have to wake him up. Just a second."

[B2] "What's his name?"

[Instructor] "His name is Tofu. You have to be very carful with him. He is very fragile and might break."

[Instructor] "Tofu can't see very well, he can only see about this far - hand about a foot in front of tofu."

[Instructor] "Do you want to see how Tofu can see colors?"

[Instructor] "So this is a special wand I made so you can play with Tofu."

[B2] "A wand?"

[Instructor] "But instead of a magical wand, it is a wand that Tofu can see." - demonstrating the wand by moving it around.

[B2] "Can I do it, can I do it?"

[Instructor] "It works better if you sit over here. Can you sit over on this side?" B2 is holding the digital paintbrush and moving it around without hitting the trigger button.

[B1] "He can see me. Can he see me now?"

[Instructor] "So, try hitting the button on the wand." Blobs appear

[Instructor] "Try holding it down and doing it." B2 draws lines on the ground with the wand"

[Instructor] "can you change the color?"

[B2] "Yeah."

[Instructor] "There you go."

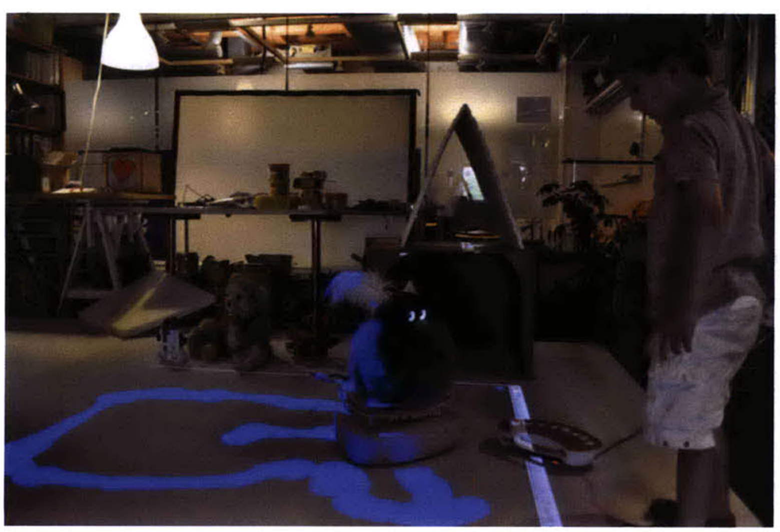
[Instructor] "Can you tell me what this button does?" Pointing to the erase button. B2 selects the erase button and try using it on the digital canvas.

[B2] "Oh, this erases it."

[B1] "Can I try"

[B1] "Hey how do you do it."

The following transcript shows the exploration of the Digital Painting interface as a control mechanism for the Tofu robot. The dialogue shows how the users go from exploring the Digital Painting behavior to exploring how the painting effects the robot. Interactions with the instructor show the way in which the robot character and control interfaces were described to the users.



After painting a path for the Tofu robot, children were able to reflect as the robot executed path following behavior.

[B2] "Ohhh"

[B1] "Awesome" - Responding to Tofu Moving a little on the ground.

[Instructor] "Ok, I turned on Tofu, so he can see the paint now."

[Instructor] "We are going to try to get Tofu in his home, ok?"

[B1] "How to we get Tofu in his home?"

[B2] "Oh, Make him see this." Pointing to the entry to Tofu's house.

[Instructor] "I hear he really likes the color green. You think we can use the color green to get him in there?"

[B1] "Green?" - B1 selects the green button on the digital palette and starts to paint between Tofu and his house.

[Instructor] "Oh, but he can't see it though. Remember, he can only see about this far, his eye sight is really bad." Holding hand about a foot in front of Tofu. B1 paints a blob in front of Tofu - Tofu drives forward on top of the green blob and dances.

[B1, B2] Laughing

[Instructor] "oh he saw it! Can you connect the two to get him in his home?"

[B1] "Where is his home.?"

[B2] "Over here."

[B1] "Thats his home?"

[B2] "Can I try". Politely reaching for the digital paintbrush, then moving the paintbrush closer and closer to Tofu. Once the brush is right in front on Tofu, B2 paints a blob to make the robot move forward and dance. B2 puts another blob down, and another. Tofu eventually is right by his home, then goes inside.

[Instructor] "Yay! So now what do you want to do?"

[B2] "Ahhhh?"

[Instructor] "Maybe try another color."

[B2] "I wan to try, Orange." Pressing the orange button - continuing to put blobs of paint down to guide the robot. Robot slams into the palette. (Laughs)

[Instructor] "Try drawing a strait line." B2 Draws a short line segment - Tofu spins into place and drives over the line. B2 draws a longer line and Tofu follow the longer line.

[B1] "Can I try." B1 Draws a short line segment - Tofu follows.

7.4 TofuDraw Study - Findings with Younger Participants

Introducing Tofu

When introduced to Tofu, both participants in both groups became much quieter and interested in the new character. Both groups also did some investigating to see what was behind Tofu, as well as looking around to see what or who was controlling Tofu. Before introducing Tofu, both groups were somewhat restless while playing with the stuffed plush toys.

Introducing Digital Paint

After explaining the Digital Painting interface, the paintbrush was handed over to the oldest sibling, who after pressing the button on the brush, would see a blob of paint - "Cool," one of the brothers said. The link between digital paint and brush was immediately obvious to the brothers, who had a strong grasp of how to paint with the digital brush. The youngest sister was still quite young and has decided to let her older sister explore the painting interface. Although the link between paint and brush is clear, the link between painting and the trigger button on the brush is not. Instead of pressing and holding the button, the older sister decides to press it momentarily, generating

Many different interaction styles were tried by children operating the Digital Paintbrush.

what seems like intermittent functionality. Both of the younger siblings eventually try the digital painting with success, the younger sister was still not quite old enough to fully grasp how to paint, but can manage to get different colored blobs to appear. Each sibling was able to paint with the interface although some with more mastery than others. Even the oldest siblings still had some difficulty in determining how to move the paint brush to obtain the desired painting pattern. The older sibling as well as the younger siblings kept moving the orientation and height of the paintbrush to influence the painting behavior. Since the behavior is only determined by the position in X and Y directions, these methods had no effect on the paintings generated.

First Steps with Tofu

After learning the basics of digital painting, the groups were asked to help get Tofu back to his home. After being told that Tofu likes the color green, both groups painted a path for Tofu without external help. Both started by painting small blobs of green to attract Tofu to each blob left like breadcrumbs. Eventually the breadcrumbs became a line which lead Tofu home. After being asked what they would like to do next, both groups used different colors to paint Tofu a path out of his home. When asked what the different colors do, both groups did not appear to understand the link between the robot's change in behavior and the change in color. The link between the robots movement and the line placement was however very clear to both groups. Collaboration between the two brothers was very civil and both were equally interested and inquisitive. The sisters did not collaborate as much and were rather independent. The age difference between the sisters made it difficult for the two to jointly explore the functionality of the painting interface. The younger sister was observant while the older sister did the majority of the exploration with Tofu. When asked wether they could make Tofu go in a circle, both groups easily were able to draw a circle that made Tofu travel around and around. When asked if they could make Tofu stop, both groups (older siblings in both cases) managed to eventually erase a section of the path to stop Tofu.

Next Steps with Tofu

After playing with Tofu and the digital painting interface, the ButtonBox and Gamepad interfaces where introduced as a different way to control Tofu. First the ButtonBox was introduced by showing the link between button states and robot behavior. Like the paintbrush interface, some of the participants had difficulty with holding the button to activate the behaviors. Instead they expected to press the button momentarily to engage the behavior. Even with the difficulty, the younger sister, who had been an observer, now became engaged in controlling Tofu. Each button became a new surprise, a new behavior to explore. Unlike the painting interface where the link between color and behavior where not very noticeable, the ButtonBox interface provided immediate feedback capable of helping identify the link between the button and the corresponding behavior. When introduced to

Even the youngest participants were able to use the ButtonBox control interface.

the gamepad interface, the older sister was thrilled to control the motion of the robot in real-time. Both groups found the gamepad controller to be engaging but also difficult to use due to the sensitivity of the controls. When comparing the different control interfaces, each seem to have been popular for different reasons. The simplicity of the ButtonBox allowed even the youngest siblings to participate in the fun and see a direct and immediate correlation to pressing each button.

Controlling the robots motion in realtime was exhilarating for the users, but also difficult to control. The painting interface enables the robots motions to be finely controlled by making a spacial plan. By observing the plan unfold, the users were given the chance to reflect on what they thought would happen in comparison to what actually happened.

7.5 TofuDraw Study - Findings with Older Participants

After interacting with the younger participants, two additional groups of older children interacted with Tofu. As with the first two groups, the older children are also two sets of siblings. Each group consisted of an older sister and younger brother. In both cases the older sister is eight and the younger brother is six. The two groups below are referred to as the first and second group to distinguish one from the other.

Introducing Tofu

As with the study done with the younger participants, Tofu was introduced to the small group of children as a friend who would like to play with them. The reaction to Tofu by the older children was very similar to that of the younger children. Even with out moving the appearance alone of Tofu generated interest and inquisitiveness in the participants.

Introducing Digital Paint

After introducing the children to the Digital Painting method, they had no problems using the technique paint on the floor. Both the first and second group were able to quickly grasp the digital painting technique and proceeded by creating different designs on the floor. Both groups approached the new technology as collaborative experience taking turns and describing to each other the way in which the Digital Painting method works. Unlike the younger participants the older user typically held both the Digital Palette and Paintbrush. Typically this was done using two hands, and occasionally by having one user hold the paintbrush and the other the palette. This pattern is in stark contrast to the younger users who would drag the palette almost exclusively by the chord connected to the palette. This difference could be due to the relatively large size and weight of the palette to the smaller users, or due to the lesser potential awareness of the fragility of objects at a younger age.

First Steps with Tofu

Both the first and second group of users had no problem understanding the link between painting interface and the robot's functionality. As with the younger participants, the motion of the robot in relation to the painted line appeared to be more salient to the users than the robots expressive response to the color of the line. It is not clear why the color to expressive behavior relationship is not as strong when using the painting interface. Although the robot's expressiveness while moving is interesting to the participants, what the robot is expressing is less memorable. This observation could be due to the subtleness of the robot's expressions in comparison to the robot's movement across the floor. Another reason could be the lack of realtime feedback from the robot during the creation of the choreographed behavior. Instead, the user must wait until after the line has been completed to observe the robot's expression. Another possible explanation involves the perceived autonomy of the robot. When following a line painted in front of the robot, the robot is participating in a dance between the child and the robot. The child creates a desired path for the robot and the robot plays the game by following. This act by the robot implies a certain amount of autonomy and cooperation on the robot's part. This autonomy in a way contrasts with having the expressions of the robot dictated by a color underneath the robot. The mismatch between these two models for the robot may cause a lack of believability when the robot's expressions are dictated by the color being driven on. A more believable cause of a fear expression would be for the robot to see something scary, causing it to stop and look scared, an act that implies the robot has an emotional response instead of the robot just being, well, a robot.

Children were able to instruct the robot to move in a circle though the Digital Painting interface.

Next Steps with Tofu

As with the younger users, the older participants enjoyed using all of the interfaces for different reasons. The older participants also enjoyed using the ButtonBox and Gamepad interface to control the robot in realtime. Being able to have realtime feedback from the buttons linked to the robot's expressions seemed to be engaging to even the oldest users in the study. As with the younger participants, the sensitivity of the Gamepad controller made it hard to control the robot's motions, resulting in sporadic and jerky motion. Even with the difficulty in controlling the robot's base, the Gamepad controller was still one of the most entertaining ways for the participants to control the robot. The younger brother in thesecond group of participants was controlling the movement of the robot while his sister controlled the expressions of the robot. As the older sister held the "think" button down, the robot began to move from side to side. As the young brother watched the robot move from side to side, he began to mimic the robot.

7.6 Design Lessons Learned from the Study

Observations made during the studies presented here have inspired many design directions and ideas on interaction design for children. Below are a few of the major observations and the implications of those observation on future versions the the system

Digital Painting Interface

Although nearly all the children eventually obtained a firm grasp on the painting interfaces operation, it was clear during the study that the design for the interface could be improved. With many of the younger participants in the study, using the painting interface was done while sitting down. In addition, the Digital Palette was seldom held by the younger users, but rather dragged around the floor. Ideally the painting experience would be performed as a whole body activity standing up. To enable this type of interaction, the digital paintbrush could be changed in form to resemble a small broom sized brush to eliminate confusion as to where the brush should be held and at what angle. Instead of linking the brush to the Digital Palette though a wire, the palette and brush could become one, or the brush could be "dipped" in small pools of color off to the side of the floor. The act of erasing appeared to be frustratingly time consuming for some of the users as well. Providing an easy mechanism for users to clear the screen rapidly and would certainly be useful given observations during the study.

ButtonBox and Gamepad

Although the link between button state and robot behavior appeared to be clear to even the youngest of users, the constant as opposed to momentary button pressing required to activate the robot's expressions was not immediately intuitive to any of the study participants. One solution for the ButtonBox would be to link the button press to audio or light to further link the need to hold the button down to activate the corresponding robot behavior. A certain change to be made on the Gamepad controller interface is a way to reduce the sensitivity of the robot's movement. When accelerating from zero to full speed, as the children often do, the Tofu and base robot tend to jerk forward. Without fine control over the joystick, jerky motion and difficulty in turing slightly is common. Ways to improve these symptoms include creating safe limits to the robots maximum velocity and setting acceleration of the robot to a less aggressive value.

8 Educational Implications

Early studies with children using the TofuDraw system and Interacting with the Mochi robot have brought insight into how children view robotic characters within a play context. In this section I describe the implications of the observations made while children engaged with the Mochi robot and TofuDraw systems.

8.1 Fantasy World and Engagement

we were able to obtain a glimpse at how children incorporate the character into the stories they generate during a group storytelling exercise.

Initial studies performed during this project aimed to explore how children make expressive robotic characters part of their fantasy-play worlds. By including the Mochi robot in a story-generating activity with a group of preschool age children, I was able to obtain a glimpse of how children incorporate the character into the stories they generate during a group storytelling exercise. The findings are very preliminary, as only one study was performed, and differences between the robotic play scenario and non-robotic play scenarios where not evaluated. The finding however to suggest that children find the Mochi expressive robotic character to be engaging and that children have no problem making Mochi part of fantasy play world shared by non-robotic plush characters.

During studies performed with the Tofu character, children where not prompted to come up with their own stories for Tofu. In all study groups, children did not verbally describe fantasy play scenarios involving Tofu or other characters. Further studies with TofuDraw could look at how the Digital Painting interface as well as the ButtonBox and Gamepad interface could be used as a tool for fantasy-play activities. Although children where not prompted to generate their own fantasy-play senarios involving Tofu, they were asked in each study to help bring Tofu back to his home. The ability of each group to acknowledge Tofu's "home" as a large cardboard box suggests that children did engage with Tofu and the box as an act of symbolizing [Nem98].

8.2 Choreography of Expressive Robots Using Tangible Interfaces

Each group of children who participated in the TofuDraw activity was able to iteratively discover the link between the digital painting interface and movement of the Tofu robot. An exception to this observation was in the case of the younger three year old sister, who was not yet old enough to make the connection. The discovery of the Digital Painting in each case involved a clear "diving-in" and "stepping-out" cycle where each time the participant alternated between immersion and reflection [Ack96], new insights were gained about the system. Although some of the participants had trouble determining the optimal way to operate the painting interface, each was able to gain mastery of the system through a process of reflection.

Although some of the participants had trouble determining the optimal way to operated the Digital Painting interface, each was able to gain mastery of the system through a process of reflection.

Using Digital Painting as a tangible interface, children successfully choreographed the motion and expression of the Tofu robot. Initial findings suggest that children found the link between the motion of the robot and the painted line intuitive. The link between the color of the line and expression was not however recognized by any of the participants. The GamePad and ButtonBox interfaces which have realtime control capabilities did however create an intuitive link between the interface and the expression of the robot. One hypothesis for this difference is the perceived autonomy when controlling the robot with the Painting interface vs. the ButtonBox and Gamepad controller, suggesting that having realtime control of the expressive robot creates an increase in perceived autonomy of the robotic character. Although the link between the Digital Painting color mapping to the behavior of the robotic characters expression is not initially intuitive, the learning of these abstract mappings is beneficial as a learning exercise.

8.3 Mimicry and Syntonic Learning

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 ones body.

During the second of the studies performed with the older participants, a young brother, age-six and his older sister, age-eight, interacted with the TofuDraw system. After exploring the Digital Painting functionality, the older sister operated the robot's expressions using the ButtonBox interface while her brother controlled the robot's motion using the gamepad interface. During one interaction, the sister activated the "Stevie Dance" on Tofu, causing it it rhythmically dance back and forth while her brother directed the robot to move across the floor. While the robot danced and moved, the younger brother, while standing up, 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, during a study with the younger group of participants using the TofuDraw system, one of the participants displayed similar mimicry behavior while using the Digital Painting interface. In this case, the participant was the older brother (age-six) from a pair of brothers who used the paintbrush after having a chance to master the interface. The participant had progressed from dropping small blobs of paint, to laying down lines to direct the robots motions. In one observed case, the participant moved his body back and forth in a rhythmic fashion while painting the line to instruct Tofu's motion.

In both cases, the mimicry behavior appeared to be inspired by the movement of the robot. Similar mimicry while using the TofuDray system suggest to a certain extent, the potential for body and ego syntonic learning as described by Papert [Pap80]. 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 ones body. Although this potential link was observed in the Digital Painting interface, which by design engages body motion, similar mimicry behavior was observed while using the

Gamepad controller which is not designed to engage the entire body.

8.4 Summary

Through interactions between children and the Mochi and Tofu expressive robotic characters, observations have been made which suggest that the characters can be a components of children's fantasy-play worlds and the behavior of those characters can be controlled through child friendly interfaces. These interfaces are designed to choreograph, or determine the characters motion and form. Through the use of interfaces mapped to the robot's behavior in realtime, and interfaces which control an editable abstraction of the robots behavior, children have demonstrated an ability to explore and in most cases master the control over these interfaces. In the TofuDraw user study, participants were observed demonstrating mimicry behavior in relation to the Tofu robot. This observation was made in two cases, each child six-years-old; one while using the realtime control interface and another while creating an abstraction of the robots control. Although preliminary, these findings suggest that the TofuDraw system could be used as a technology for engaging in fantasy-play activities and have the potential for body and ego-syntonic learning of the links between choreographing robotic motion and expression and abstract interfaces to control robotic expression and motion.

9 Future Work with TofuDraw

This thesis has introduced a way of incorporating expressive robotic characters into physical fantasy-play environments for children. Through a set of custom interfaces, I have created a mechanism that provides children with the ability to choreograph the motion and expression of these robotic characters. This section explores how the existing TofuDraw system could be further developed as a tool for enabling technology augmented fantasy-play environments.

9.1 Expressive Character Design

The Tofu and Mochi robots used in the TofuDraw and related storytelling studies have a specific set of expression and mobility capabilities. The choice to include these capabilities was made using a very loose set of guidelines based on animated character design principles. Although it has been assumed that expressive characters are better than non-expressive characters, this direction has only been minimally explored with this project. Future experiments could utilize characters with a spectrum of expressiveness as a means to explore which expressive capabilities are more salient and engaging during interactions. The presence of dynamic eye motions and mobility both appeared to be high impact expressive robot character qualities during studies with children. Further qualities to explore include, but are not limited to, basic facial expressions, scale, and of basic body language forms of expression.

Future experiments could utilize characters with a spectrum of expressiveness as a means to explore which expressive capabilities are more salient and engaging during interactions.

9.2 Future Directions with Digital Painting

Although children using the digital painting interface were in most cases able to grasp the interface functionality, the device could be improved in many ways. In some cases users were confused by the link between the orientation of the digital paintbrush and the painting behavior. Users also would sit while using the digital painting interface instead of standing and holding the digital paintbrush and palette. Interaction patterns as a result included body repositioning and in many cases dragging the digital palette around the floor.

By creating a large brush that could be manipulated while standing, users could easily move around while holding the brush.

An interface alternative to explore would also leverage the physical affordances of painting, but on a different scale. By creating a large brush that could be manipulated while standing, users could easily move around while holding the brush. Creating a mental link between the brushes contact with the floor and the act of painting the device would also more closely resemble the physical affordances of painting. The digital palette interface could be replaced by a set of color selection buttons on the large brush itself or perhaps a color on the floor that the brush is "dipped" into.

The digital painting interface can be considered a physical way to manipulate digital data. Further exploration of this paradigm within the digital painting context could enable interesting interactions. For instance, a camera form factor device could enable users to capture a painted section made with the digital paintbrush. Different modes on the camera could allow users to "paste" the copied painting capture using the same camera-like interface.

9.3 General Future Directions

This thesis presents technology designed to enable children to choreograph the behavior of expressive robotic characters. Unlike a puppet with actual strings, expressive robotic characters can be controlled in a multitude of ways through digital interfaces. This thesis presents only a few mechanisms for controlling the robot. Future explorations could look at other ways to control the robotic characters to enable certain types of interactions. Such interfaces could include expressive robots that respond to objects in the physical environment as well as people. A robot could, for instance, be afraid of the

Unlike a puppet with actual strings, expressive robotic characters can be controlled in a multitude of ways through digital interfaces color red or a certain person when wearing a mask. Other interfaces could enable choreographed behaviors to be stored into an object by association. If multiple robot were introduced into a system, interfaces could be created that enable the two robots to interact in an interesting way. For instance, one robot could always follow another when wearing the "follow hat." Other modalities could make one robot always express the opposite emotion as the other. The use of expressive characters in this thesis is just scratching the surface of what is possible.

10 Appendix A: Supplemental Material

11.1 CAD Files

All Mechanical CAD files used to create the TofuDraw system, related interfaces, and supplemental robots can be found here: http://web.media.mit.edu/~rwistort/MSThesis/CAD.zip

11.2 Source Code

A copy of the python arduino, embedded C, and java source code used to control the TofuDraw system, related interfaces, and robots can be found here: http://web.media.mit.edu/~rwistort/MSThesis/Code.zip

11.3 Media

Digital media for the TofuDraw system and related robots can be found at the following address. Media includes high resolution still images, demonstration videos, and general documentation media for the project. http://web.media.mit.edu/~rwistort/MSThesis/Media.zip

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