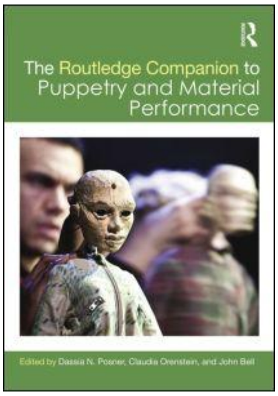

The Routledge Companion to Puppetry and Material Performance

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Programming Play

Publication details
https://www.routledgehandbooks.com/doi/10.4324/9781315850115.ch27
Elizabeth Ann Jochum, Todd Murphey
Published online on: 15 Jul 2014

How to cite :- Elizabeth Ann Jochum, Todd Murphey. 15 Jul 2014, *Programming Play from:* The Routledge Companion to Puppetry and Material Performance Routledge
Accessed on: 02 Oct 2023
https://www.routledgehandbooks.com/doi/10.4324/9781315850115.ch27

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Programming Play

Puppets, Robots, and Engineering

Elizabeth Ann Jochum and Todd Murphey

> Art lies halfway between scientific knowledge and mythical or magical thought.
> Claude Lévi-Strauss (1962: 22)

In this chapter we introduce the *Pygmalion* Project, our collaboration between Northwestern University, the Georgia Institute for Technology, the University of Colorado, and Disney Research to develop a robotic platform for controlling marionettes. While engineers at Carnegie Mellon University, Nanyang Technological University in Singapore, and National Chiao Tung University in Taiwan have experimented separately with automating marionette and glove puppets, many efforts to combine robots and puppets have focused on using mechanical limbs to reproduce human and animal motions exactly.[1] These automated puppets often appear rigid and perfunctory and fail to stimulate the imagination in the same way that puppets operated directly by live puppeteers can. In the *Pygmalion* Project the robots are not the puppets, but rather the agents that operate the puppets. Our goal is to emulate the control technique of human puppeteers to develop automated puppets that are capable of dynamic movement typically beyond the range of traditional animatronics – such as walking and flying. Using the natural dynamics of marionettes, where puppets create the illusion of life through the art of indication rather than precise mechanical reproduction, we anticipate that our robotic marionette platform will allow for a wider, more artistic range of automated motions for entertainment robots.

Since antiquity, both artists and engineers have been interested in the creation and animation of material objects that create the illusion of life. Through the artful imitation of human and animal motions – using either the techniques of traditional puppetry (objects operated through direct human manipulation) or automated motion (objects that move autonomously) – inanimate objects succeed in creating compelling illusions because of what Bert States calls "binocular vision" (1985: 8). In the theatre, States argues, the spectator has the ability to "hold in mind two categories – that of the real and that of the imaginary – that are fused into a single phenomenon" (States 1985: 169). Binocular vision is what allows theatre audiences to grant fictive life to characters or objects based on their behaviors and the performance setting, encouraging spectators to project psychology and emotions onto human actors or inanimate objects. Binocular vision is especially pronounced in puppetry and productions that feature robot actors; but the nature of the theatrical illusion is problematized because, unlike human actors, puppets and robots are inanimate objects that simultaneously occlude and expose their artificiality, purposefully challenging distinctions between the real and imaginary (Bergamasco and Ghedini 2010: 731).[2] While a human actor never has to prove their "liveness" to a spectator, puppets and robots hover in a liminal space between the animate and the inanimate and must therefore work differently than human actors to provoke binocular vision. In marionette performance, puppeteers create the illusion of life by directing the dynamic swing motions of the marionette to generate movements that indicate human and animal behaviors but do not copy them precisely. Conversely, robots and other animatronics have typically eschewed dynamic motions in favor of ultrarealistic design, which results in objects that may look lifelike but have a limited range of motion. This approach raises expectations about how believably and convincingly the object should be able to perform, challenging the spectator's binocular vision by presenting an illusion of life that can sometimes appear frightful or uncanny.

Following Ernst Jentsch's 1906 essay "On the Psychology of the Uncanny," Freud defines the uncanny as the emotional response of fear or dread that arises from an encounter with a person or object that provokes doubt about its liveness (Freud 1919 [2003]: 135). Freud argues that specific situations provoke a strong sense of the uncanny – for example, "when the boundary between fantasy and reality is blurred, when we are faced with the reality of something that we have until now considered imaginary, when a symbol takes on the full function and significance of what it symbolizes" (Freud 1919 [2003]: 150). If States's binocular vision arouses delight in the simultaneous perception of "that of the real and that of the imaginary," then the uncanny can be understood as the inverse of that experience, where the spectator becomes frightened or anxious because of the uncertainty surrounding whether the object is living or dead, real or imagined. Recognizing the implications for robotics, Masahiro Mori coined the term "uncanny valley" to define this problem for robot engineers: human beings delight in the illusion of inanimate objects that appear to be alive, such as dolls and puppets, but if an object reaches a remarkable likeness without actually achieving liveness, the illusion is no longer pleasurable but disturbing (Mori 1970 [2012]: 99). Unlike robots, many traditional puppets manage to avoid the uncanny valley through design choices and the implied presence of the human puppeteer.[3] Because a puppet never has to convince a spectator of its autonomy, spectators can enjoy the illusion without experiencing uncertainty about the puppet's liveness. For example, Mori cites *bunraku* as an art form where the audience becomes "absorbed" in the performance and is able to "feel a high level of affinity for the puppet" despite the puppets' physical resemblance to humans (Mori 1970 [2012]: 99). We might say that for puppets, binocular vision supersedes the experience of the uncanny. Unlike puppets, robotic actors always risk appearing uncanny because they are designed to perform autonomously and independently from a human operator. The tendency towards the uncanny is furthered when robots are designed to physically resemble humans, such as the Geminoid F (discussed by Cody Poulton in Chapter 25). To create compelling theatrical illusions that provoke binocular vision, engineers would do well to design robots that avoid appearing uncanny.

In both puppetry and robotics, expressive movement is an integral aspect of mimesis, influencing how deftly the illusion of life is created and sustained. Joseph Roach observes that "expressive movement is becoming a lingua franca, the basis of a newly experienced affective cognition and corporal empathy. Mimesis, rooted in drama, imitates action; kinesis embodies it" (Roach 2010: 2). Recognizing the importance of expressive movement to puppetry and robotics, we might extend the metaphor of movement as a *lingua franca* for communication and interaction between humans and robots, and in particular for robots tasked with imitating human motions. Mori argues that movement is fundamental to how humans perceive animate and inanimate objects, proposing that the presence of movement "changes the shape of the uncanny valley graph by amplifying the peaks and valleys" (Mori 1970 [2012]: 99). The ability to generate expressive movement is directly related to how readily humans develop an affinity for inanimate objects. Mori's consideration of movement articulates for engineers a truth long understood by puppeteers: how an object moves, rather than its physical appearance, provokes binocular vision and creates the illusion of life.

The field of puppetry has a rich history of generating expressive movement that suggests the illusion of life without precisely copying human or animal motions. While puppetry is rooted in mimesis (puppets are imitative of human behavior in appearance), puppets operate according to a different set of physical laws than the creatures they imitate. From the perspective of movement, puppets are interesting because they partly resist a puppeteer's attempts to direct them: puppeteers are forced to reach a compromise with the physical dynamics of the puppet to create believable and expressive characters. This tension was explored in Heinrich von Kleist's 1810 essay "Über das Marionettentheater" ("On the Marionette Theatre"), here summarized by Kenneth Gross:

> The puppeteer knows he cannot control each limb separately, and thereby imitate in perfect detail the natural movements of human bodies. Rather, the manipulator learns to yield himself to the specific weight, the pendular motion and momentum of that thing suspended from strings. That's where the puppet's soul is found, in its merely physical center of gravity, which is the line of its spirit.
>
> (Gross 2011: 63)

The puppet's power of artistic expression is therefore not determined by how well it mimics human behavior, but rather by its ability to abstract the human experience and throw it into a type of relief, offering an artistic projection of a recognizable world from which we are partly or wholly free. That puppetry privileges artful imitation over precise replication confirms States's notion of binocular vision, grounding puppetry's underlying aesthetics more firmly in the Aristotelian notion of theatre as the imitation of an action. For marionettes, puppeteers have developed approaches that enable them to balance the dynamics of the puppet against the need to execute expressive choreography that convincingly imitates – but does not replicate – human and animal motion. Because puppets resist mimicry, they are capable of creating the illusion of life (or a different kind of life) in a way that pure mechanical replication does not. For this reason, we anticipate that entertainment robots might benefit from incorporating puppet-inspired design choices: not limited by the need to realistically replicate motions, engineers can learn from puppetry how to generate motions that provoke binocular vision and avoid appearing uncanny.

Traditionally, engineers have approached the task of imitating movement through mechanization, powering the motions of robotic limbs through individual motors or hydraulics located inside the puppet. Because of the tremendous difficulty of reproducing complex movements such as walking or dancing, entertainment robots are often heavily stabilized and equipped with a limited set of pre-programmed gestures. This reduced set of behaviors ensures that the robotic actors are reliable and stable, but the mechanisms involved with replicating the motions make the robots heavy and difficult to work with. Because these robots attempt to realistically mimic facial expressions and refined gestures, their jerky, mechanical motions are jarring and appear uncanny; the contrast with their lifelike appearance provokes uncertainty over whether the object is alive or not. Engineers who wish to develop mechanical performers that are better able to imitate the human experience must learn how to create the illusion of life through other means. Our research suggests that one way to achieve this is through dynamic motion that does not aim at precise mimicry. We use puppetry as a model for creating expressive automated robots that avoid the limitations of conventionally automated figures. For entertainment robots, kinesis is the new mimesis.

The *Pygmalion* Project is a collaboration begun in 2007 between artists and engineers to develop an automated platform for operating and controlling marionettes. After preliminary conversations with puppeteer Jon Ludwig at the Center for Puppetry Arts in Atlanta, we devised an experiment that uses string marionettes as a model for developing a new approach to automated motion. Our approach is fundamentally different than that of traditional animatronics, androids, and automata: we automate the physical motions of the human puppeteer and the forces outside of the puppet body rather than powering the motions from within the puppet. The robots in the *Pygmalion* Project are not the actors and do not appear onstage, but like human puppeteers, they act as the external agents of puppet motion. Removing the machinery from the puppet body may result in automated motion that is less rigid and more graceful because the sources of automation are indirect and hidden from view. Furthermore, the use of traditional marionettes invites the phenomenological gaze – or binocular vision – normally reserved for puppets (rather than robots), thereby helping our system to avoid the uncanny. Marionette puppetry has proven to be a useful method for investigating the dynamic, interactive processes between automated machines and passive agents, and represents a novel approach to automated motion that avoids the trappings of pure mechanization.

The Pygmalion myth – the story of the Greek sculptor who carves an ivory statue of a woman, which is then magically brought to life – provides the plot for our play and the title of our project. We were interested in a narrative that prompted reflection about the nature of our research: the relationship between humans and their attempts at creation. The metamorphosis in Pygmalion is a movement from the inanimate towards the animate, a theme that resonates in both puppetry and robotics. We determined that the story could be told though movement alone, using only two characters, and that the choreography for each puppet could be isolated. The last feature would prove important once the design for the system was finalized.

At the time of writing this essay, we have completed a prototype and programmed the robots to perform sections of the play. Our system was featured at the Museum of Science and Industry in Chicago during National Robotics Week in 2012 and 2013, where we performed short choreographic segments and demonstrated the user interface. Visitors were invited to interact with the system and design marionette choreography in real time by using software that translates their movements into choreographic sequences for marionettes. While we have not yet realized a full production, our ongoing research has led to useful findings about the complex task of automating human motion and the profound difficulties involved with computing mathematically what a puppeteer does intuitively. Our results suggest how the developers of entertainment robots might use puppetry as a model for designing and programming robotic performers that are more dynamic than the current generation of entertainment robots.

Kinesis in the age of mechanical reproduction

Automated mechanical figures have delighted audiences from antiquity to the present, but because of the technical and conceptual difficulties involved with replicating human and animal locomotion, these figures have traditionally focused on reproducing small, precise gestures, such as speaking, drawing, or playing musical instruments, rather than ambulatory movement, such as dance or acrobatics.[4] The automata of Heron of Alexandria (first century BCE), Leonardo Da Vinci (fifteenth century), Jacques de Vaucanson (eighteenth century), and Henri-Louis and Pierre Jaquet-Droz (eighteenth century) are forerunners to contemporary entertainment robots found in stage productions and theme parks. Because we are interested in kinesis, we can divide entertainment robots into two categories according to how they move: automated and tele-operated figures.

Automated figures – or automata – imitate human and animal behaviors and gestures, and although they appear to operate independently and without human agency, they require a human operator to set them in motion – for example, by turning a crank or pressing a button. Automated figures can be operated by pneumatics (pressurized gases) or hydraulics, through a system of springs and pulleys, or by clockwork mechanisms. Animatronic figures, such as those found in Disney's "The Hall of the Presidents," are automata that are powered electronically and rely on hydraulics and individual motorized joints to move. They operate according to a predetermined program run on a computer that determines the time, sequence, and duration of their movements. While automated figures might feature a variety of programmed movements – Vaucanson's life-size flute player (1739) could play 12 different melodies and Jaquet-Droz's "The Draftsman" (1771) could sketch four different drawings – their range of expression is limited to a predetermined set of behaviors. The benefit of these types of machines is that the performances are reliable over time; however, their rote performances do not always provoke binocular vision.

Tele-operated figures are mechanical figures in the shapes of humans, animals, or other fanciful creatures operated in real time by a human operator who controls the movements remotely. Like automata, these figures have a narrow range of expression that is limited by a set of preprogrammed expressions and gestures. However, because the figures are operated by human agents, they can often appear to be more interactive and expressive than their automated counterparts. Tele-operated figures have more in common with puppets because they are operated by external agents.[5] Examples of tele-operated robots are the Geminoid F and the Disney/Pixar animatronic *Wall-E* robot, each of whose expressive limbs and facial gestures simulate human motions and behaviors through the agency of human "puppeteers" who tele-operate the puppets remotely.

Because of the exigencies of live performance, including the presence of human actors and a live audience, the developers of entertainment robots must decide how to design and program robots that create pleasurable theatrical illusions without compromising the stability of the system or the safety of the audience. In some ways, theatre is an ideal venue for tele-operated robots because a stage production is a narrowly defined domain in which automated figures can excel. In a scripted production, the dialogue, technical cues, and choreography of the other actors are predetermined and guided by a human agent (the stage manager), who oversees the event from offstage. This approach makes it relatively easy to insert tele-operated robots into a live performance alongside human or other robotic actors. However, introducing fully automated robots into this setting is a more difficult task and often involves a trade-off between more dynamic behaviors – such as responsive facial gestures and speech which require a human operator – and those that favor more stable and repeatable motions not requiring an operator. The latter performances are unvarying, which often leads to motions that appear dull or predictable. In both cases, tele-operated and fully automated figures are heavily stabilized, and because of the machinery involved, are cumbersome to work with. The combination of weight and safety concerns and motion-control challenges makes it difficult to create compelling theatrical illusions that provoke binocular vision.

In terms of movement, both automated and tele-operated robots are similar to rod puppets, where movement is defined in kinematic, geometric terms – that is, by precisely mapping the motions of joints to the motions of the puppet. In rod puppetry, the puppeteer provides stability for the puppet, and the movements are directly controlled by the geometry of the human-powered rod. Programming a stabilized robot to reproduce these gestures mechanically is a rather straightforward engineering task (as demonstrated by Disney's Audio-Animatronics), but because there is no human intention or artistry powering the motions, the resulting movements look mechanical or rigid. We might call this a kinematic version of Mori's uncanny valley, where the absence of human feeling and impulse make it nearly impossible for mechanical figures to communicate any truths other than mechanical ones.

How is it possible, then, that Kleist can locate a marionette's soul in its "merely physical center of gravity," while animatronics and other entertainment robots are habitually perceived as soulless? Part of this can be explained by the presence of the human puppeteer, who enters into the gravity of the marionette, allowing "his own human feeling and impulse to be drawn toward and translated through the inanimate body, finding a home for them there, making the puppet itself into an actor" (Gross 2011: 64). But we might also suggest that puppets avoid appearing mechanical precisely because they resist perfect imitation. This is especially true for marionettes, where the distance between the puppeteer and the puppet and the indirectness of the control system make it difficult to replicate precisely human or animal motions. Because marionettes are controlled indirectly by strings (rather than by rods or human limbs), they present a different problem for automating motion than a stabilized automaton seated at a desk or playing a piano.

To automate the motion of a marionette, we cannot program a motor to move the individual joints directly. Rather, we must approach the problem indirectly by considering how the human puppeteer interacts with the puppet to control its movements – balancing the need for descriptive motions against the reality of the physical motions – and automate that process. Focusing on the indirect control of the human puppeteer, we account for the marionette's unique properties by using an approach called "optimal control." In this approach, the puppet's geometric movements are used to specify how and when a robotic puppeteer should be programmed to exert forces on the puppet in order to create the desired motion. To represent a person walking, we start with the marionette body and calculate how to operate the strings and controller in a way that best creates the illusion of walking, given that a marionette cannot precisely reproduce human locomotion. For engineers, optimal control is an essential step for programming robots that are able to navigate their environment independently. Because engineers want to design robotic systems that can move and operate in the real world, and human puppeteers have demonstrated a reliable ability for controlling dynamic objects in the physical world, puppetry makes a good test bed for exploring these issues.

Marionettes have significantly more degrees of freedom than other types of puppets, albeit far less than a human body: depending upon the number of strings, a typical marionette has between 45 and 60 degrees of freedom, while a healthy human possesses a number far greater than that. And yet, in the hands of a skilled puppeteer, marionettes are capable of a wide range of expressive and nimble choreography that emulates human movement. Rather than replicate the mechanical processes of a person walking, a marionette indicates walking, using the ground only as reference point and not as a physical constraint. As Kleist observed, marionettes appear immune from gravity's forces: "Puppets need only to touch upon the ground, and the soaring of their limbs is newly animated through this momentary hesitation" (Kleist 1810 [1972]: 24). Within this abstracted framework – where puppets operate according to a different set of dynamic and aesthetic laws than humans and humanoid robots – puppeteers have developed a system to control figures that is artful, stable, and reliable. This is the process that we emulate.

The *Pygmalion* Project

To understand how marionettes are operated, we met with puppeteers at the Center for Puppetry Arts in Atlanta. From puppeteer Jon Ludwig, we learned of an approach to designing puppet motion known as the "Imitate, Simplify, Exaggerate" method: imitate an observed behavior, simplify the motion to its basic components, and exaggerate the behavior to an appropriate level of animation that creates the illusion of that motion. To translate this approach into engineering terms, our first task was to describe this three-step process in computational terms. To do this, we had to model mathematically what a puppeteer does intuitively.

Ludwig describes how marionette choreography is divided into small units of motion, each lasting a specific amount of time (Egerstedt et al. 2007: 192). Puppeteers coordinate the timing of a motion so they can interact with other puppeteers, sometimes collaborating to control a single marionette or groups of puppets, ensuring that the marionettes remain animated throughout the performance. Scripts of puppet plays describe the action using four parameters: temporal duration, agent, space, and motion (i.e., when, who, where, and what). These motions are grouped and executed according to counts that specify when each motion begins and ends. During rehearsals and performance, the puppeteer makes decisions about the use of force, dynamics, and movement qualities that determine the expressive characteristics and the overall visual effect, handling complex choreographic sequences and solving problems of uncertainty. Using puppetry as our model, we developed robotic controllers and corresponding software that would replicate this process as closely as possible.

Unlike the puppeteer who can rely on a combination of heuristics and improvisation, engineers must work with comparatively simple building blocks to design marionette choreography. For the *Pygmalion* Project, we used two interdependent approaches: we created a software program called "Trep" that mathematically translates human motions into feasible puppet choreography, and we designed a robotic platform for controlling the marionettes (Johnson and Murphey 2007; Martin et al. 2011). Trep programs the robots to "perform" a marionette play, essentially enabling the robotic controllers to assume the role of a human puppeteer. Unlike traditional puppetry, however, we cannot rely on a human agent to interpret the kinetic "script." In a fully automated system, the marionette and its robotic controllers remain passive and mechanical; therefore, we must consider other factors, such as how many robots should operate one puppet and how to coordinate the movements of several robots controlling a single puppet. Unlike robots, puppeteers rely a great deal on intuition, and they are continually aware of where the audience is seated and of the positions of their left and right hand at any given moment. One of the most challenging parts of the experiment was coordinating and controlling the movement and efforts of the robotic controllers to approximate this level of intuition and awareness.

We devised the choreography with professional dancers – an approach not dissimilar from digital or puppetry – to generate a set of data points that would provide a mathematical "script" to start with. First, we encouraged the dancers to move with their natural gait and full range of motion; we then simplified the choreography to a level that would sufficiently communicate the story and recorded the choreography using a motion-capture system (see Figure 27.1). This system uses infrared sensors to track individual points attached to the dancer's body that record each motion.[6] From the data, we calculated the speed, duration, and forces for each movement and choreographic sequence and used this information to develop software that would

Figure 27.1 Dancers Stephen Loch and Stephanie Johnson (Brooks & Company Dance) performing choreography that was recorded using motion-capture technology; Georgia Institute for Technology, Atlanta (January 2009). Photo courtesy of the authors

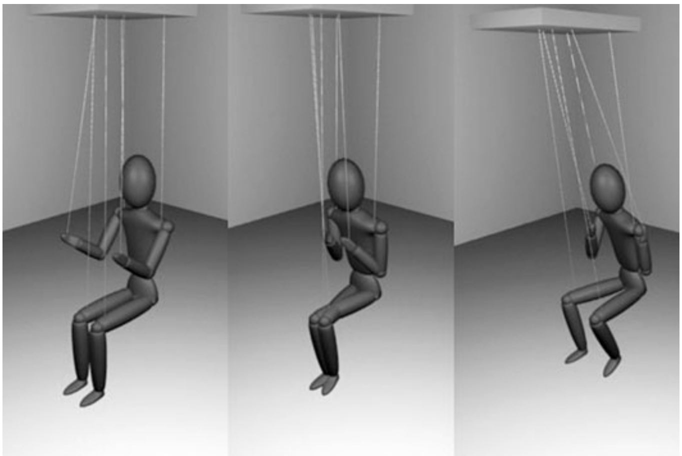

Figure 27.2 A computer rendering of marionette choreography based on motion-capture data and simulated using the original Trep software program. Image courtesy of the authors

translate human motion into abstracted marionette motion. Trep software uses algorithms to determine how to program each individual string attached to the marionette and simulates what this motion will look like using computer animations (see Figure 27.2). The "inputs" are then used to program robotic controllers that, like a human puppeteer, control the marionette by pulling on passive strings from above.

By indirectly operating the puppet, we are able to create expressive, automated puppet motion without mechanically reproducing human motions.

One might ask why we did not use marionettes to choreograph the play from the outset. Wouldn't it be simpler to use the motion-capture system to record the motions of marionettes directly operated by a professional puppeteer? The answer is that this approach would have sidestepped the more difficult – and more interesting – question of abstraction. As marionettes have fewer degrees of freedom than humans, their movements are already abstracted. Because we are interested in exploring kinesics – that is, understanding what motions are recognizably "human" and can be reliably reproduced using a minimum amount of effort and control – it was necessary to begin with the fullest range of dynamic and expressive motion possible.

Originally, we intended to control the puppets using two pivoting mechanical arms equipped with motor-powered winches for operating the marionette strings.[7] While this design partially imitated the process of a human puppeteer, it was limited because the marionettes could not traverse the stage as human-operated marionettes can. In some respects, this early design was as limited as the heavily stabilized systems we were trying to avoid because fixed robotic arms cannot approximate the fluid, dexterous, and extensive range of motion of a human puppeteer. In 2008, we began collaborating with engineers at Disney Research to develop a more flexible system for controlling the *Pygmalion* Project marionettes. We first experimented with the design of a single, freely moving robotic controller operating a single-stringed butterfly marionette. This design enabled a range of motion that more closely approximated the motions of a human puppeteer: the robotic controller (and, by extension, the marionette) could move around the entire stage fluidly and quickly, although not very reliably. To operate larger, heavier, and more articulated marionettes would require a redesign of the robotic controllers.

Following the butterfly experiment, we replaced the robotic arms of the original design with a custom-designed metal chassis equipped with individual winches for operating the strings and separate motors to drive around the stage (see Figure 27.3). A unique feature of the design is that the robotic controller is suspended from above using magnetic wheels that attach to a plastic "roof" covering the stage. This allows for a significantly wider range of motion than the original design, increasing opportunities for locomotion for the robot and the suspended marionette. The robot has three main functions: to move around the stage synchronously; to bear the weight and force of the puppet; and to reliably animate the limbs of the puppet using winch-operated strings. After early experiments with lightweight objects, such as a ball and a plastic skeleton, we determined that each puppet would require more than one robotic controller to operate it. Currently, a single human-shaped marionette is controlled by three robots attached with six strings at fixed points: two head strings, left forearm, right forearm, left knee, and right knee.

We approach the task of imitating human movement from two directions: automated motion and tele-operated motion. For automated motion, we use Trep to replicate as closely as possible the original choreography recorded from the human dancers.[8] Working with short choreographic phrases, we can learn which motions are the most aesthetically interesting and stable; however, controlling the natural swing of the marionette in between movement phrases is challenging. The second

Figure 27.3 Three robotic controllers operate a wooden marionette suspended from a plastic ceiling that covers a stage at the McCormick School for Engineering at Northwestern University: the robots each control two puppet strings and collaborate with each other to generate marionette motion; Evanston, Illinois (January 2011). Photo courtesy of the authors

approach involves tele-operating the robots in real time using remote controls. This allows us to experiment with the system more directly, as a puppeteer would operate a marionette controller, only without the tactile feedback that a puppeteer senses when controlling a marionette. The lack of feedback makes it difficult to develop an intuition for operating the puppets. In light of this limitation, we have experimented with Microsoft's Kinect®, a motion-tracking system, to record movement and reproduce the motions using Trep.[9] This method of tele-operation provides a more intuitive interface that allows users to design choreography in real time and observe the effects of their movements on the marionette. Kinect has proven to be a useful tool for designing animations in 2-D and virtual environments (Moore 2012), and our system demonstrates how it can be used to animate motion for inanimate objects in the physical world.

Currently, we are experimenting with variations of the automated marionette system. At Disney, engineers are working with lightweight marionettes equipped with individual motors on the puppet joints to create more controlled and defined movements; the forces created by the individual motorized joints help to stabilize some of the swing dynamics of the marionette. In our lab at Northwestern, we continue to develop the *Pygmalion* choreography using only the robotic controllers and are focusing on grouping together longer choreographic phrases. In addition, we are using the marionette platform to conduct other research experiments concerning optimal control and human-robot interaction.

Puppetry and future entertainment robots

From an engineering perspective, the most significant aspects of a puppeteer's process are coordination, improvisation, and intuition. Learning to coordinate the movements of robots so that they perform synchronously and collaboratively is a challenge for our experiment, in particular, and for robotics research, in general. For puppeteers, this process happens intuitively: in the direct-contact horse puppets Handspring Puppet Company designed for *War Horse* (2007, National Theatre), spectators witness how skillfully three puppeteers can instinctively and silently interact with one another while controlling a single puppet, collaboratively creating the illusion of life through the artful manipulation of an inanimate object. Designing automated systems that operate with a comparable level of collaboration and intuition remains a difficult task. Our research demonstrates that puppetry can be a powerful tool for exploring these complex processes. Puppetry is not only a metaphor for mechanical motion but also a useful method through which we can investigate the dynamics of expressive movement and its influence on binocular vision and the uncanny.

The *Pygmalion* Project is an example of how emerging technologies might be combined with well-established art forms to create new types of performing objects. Invariably these new technologies will prompt discussion concerning the relationship between the human artist and the performing object. Just as automata and animatronics challenged traditional notions of human agency by distancing the live human puppeteer from the act of animation, our automated marionette platform further distances the human artist from the live performance. The absence of a human puppeteer is potentially problematic for marionette puppetry, where the visual aesthetics are so profoundly intertwined with the physical relationship between the human puppeteer and the performing object. However, automated marionettes will not eliminate the need for human artists any more than robots have eliminated the need for human labor or puppets have eliminated the need for human actors. Rather, just as industrial robots changed the type of work that humans could do and empowered them to do other things, and just as puppets continue to artfully imitate the human condition without replacing human performers, entertainment robots will enable new types of performances and theatrical illusions. Automated marionettes invite us to consider how human puppeteers might negotiate new technological interfaces to enter the gravity of the marionette and how such technologies might shape the future of live performance.

Acknowledgments

This material is based upon work partially supported by the National Science Foundation under Award IIS-0917837. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the author(s) and do not necessarily reflect the views of the National Science Foundation. The robotic system was developed in collaboration with Lanny Smoot at Disney Research (patent pending). Choreography was developed with dancers from the University of Colorado and Brooks & Co in Atlanta, Georgia. The authors wish to thank Oliver Gerland III and Jon Ludwig for their insight and contributions. Photo credits: Elliot Johnson, Todd Murphey, and Elizabeth Ann Jochum.

Notes

1 See Chen et al. (2005); Hu et al. (2009); and Yamane et al. (2003).

2 For further discussion of "binocular vision" in puppetry, see Tillis (1992).

3 Jurkowski (1988: 55) defines puppetry as:

> a theatre art distinguished from the theatre of live performers by its most fundamental feature, namely that the speaking, acting subject makes temporal use of vocal and motor sources of power which are outside it, which are not its own attributes. The relationships between the subject and its power sources are constantly changing, and this variation has essential semiological and aesthetic significance.

4 Kang (2011) describes the Western fascination with automata and humanoid robotics, tracing the intellectual, cultural, and artistic representations of the automaton from antiquity to the present.

5 Following Jurkowski's definition, tele-operated figures would be considered puppets because they require an outside force to animate them but automated figures would not.

6 Motion capture is used to generate computer graphic images in animation and film and has been adapted for video gaming and home animation with the Microsoft Kinect®.

7 The initial design was not unlike those used in Chen et al. (2005) and Yamane et al. (2003).

8 Videos of the *Pygmalion* Project are available at <http://vimeo.com/channels/numarionette>.

9 Kinect® is a gaming console that functions as a motion-capture system. The portable device has been used in many virtual simulations and animations. See Moore (2012).

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