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TITLE

Programming Play: Puppets, Robots, and Engineering

ABSTRACT

In this chapter we introduce the *Pygmalion Project,* our collaboration between Northwestern University, Georgia Institute for Technology, University of Colorado, and Disney Research that utilizes puppets to explore the mechanics of movement. We use puppetry as a model for situated, embodied systems (robots) and apply this puppet-centered approach to relevant problems in engineering such as dynamic modeling and motion control. While engineers at Carnegie Mellon University, Nanyang Technological University, and National Chiao Tung University have experimented separately with automating marionette and glove puppets, efforts to combine robots and puppets have traditionally focused on precisely mimicking physical processes, where mechanical limbs

attempt to reproduce human and animal motions exactly.[1] As performers, these automated puppets are limited because their movements appear rigid and perfunctory. The *Pygmalion Project* demonstrates how developers of entertainment robots might use puppetry to address these limitations through the creation of a robotic marionette platform. Our research suggests that puppet-inspired robots can allow for more expressive automated movement that is not constrained by mimicry-based approaches, and proposes a new paradigm for entertainment robotics.

In the *Pygmalion Project* the robots are not the puppets, but rather the agents that operate the puppets. This approach, which emulates the indirect control of human puppeteers, results in automated puppets that are capable of dynamic movement such as walking and flying—motions that are typically beyond the range of traditional animatronics because they are heavy and unstable. 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 more artistic automated motions. Rooted in puppetry, these robot-controlled puppets have a wide range of physical expression and are capable of interacting more fluidly with human operators and spectators than traditional animatronics.

INTRODUCTION

Illusion is the first of all pleasures.

-Oscar Wilde

Theatre is a mimetic art—it is primarily engaged with the artful imitation of the human experience—and illusion is central to mimesis. Since antiquity, both artists and engineers have been interested in the creation and animation of material objects that present 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." In the theatre, States argues, the spectator has the ability to "hold at once two categories in mind—that of the real and that of the imaginary—which are fused into a single phenomenon" (States 1985: 69). While binocular vision is pronounced in puppetry and productions that feature robot actors, the nature of the theatrical illusion is problematized because, unlike human actors, puppets and robots are material objects that simultaneously occlude and expose their artificiality (Bergamasco *et al*. 2010).[2] This paradox presents a challenge for puppets and robots, as they risk appearing frightful or uncanny.

Freud defined 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 liveliness (Freud 1919). Recognizing the implications for robotics, Masahiro Mori coined the term *uncanny valley* to define this problem for engineers: we delight in the illusion of inanimate objects that appear to be alive, such as dolls and puppets, but if a performing object reaches a remarkable likeness without actually achieving liveliness, the illusion is no longer pleasurable but disturbing (Mori 1970). Unlike robots, traditional puppets can avoid the uncanny valley in part because they are controlled by a separate agent.[3] Because a puppet never has to convince a spectator of its autonomy—the puppeteer's presence is implied even when unseen by the audience—we can enjoy the illusion without experiencing uncertainty about the puppet's autonomy. A robotic actor, however, always risks appearing uncanny because it is designed to perform independently from its human programmer. The tendency towards the uncanny is furthered when robots are designed to physically resemble human actors, such as the *Geminoid F* (discussed in Cody Poulton's essay in this book). To create compelling theatrical illusions, engineers must design robots that avoid the uncanny valley.

Theatre is also a kinetic art. The physical movement of actors—whether human or mechanical—is central to the act of mimesis. In both puppetry and robotics, expressive movement is an integral aspect of the theatrical illusion, influencing how deftly the illusion of life is created and sustained. Performance studies scholar Joseph Roach observed 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 theatrical illusions, we might extend the metaphor of movement as a lingua franca for communication and interaction between humans and robots, and in particular for robotic actors tasked with imitating human motions.

The field of puppetry has a rich history of creative movement that suggests the illusion of life. 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 puppet to create the illusion of life. This tension was explored in Heinrich von Kleist's 1810 essay "Über das Marionettentheater," 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. 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 will benefit from incorporating puppet-inspired design choices.

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 body. Because of the tremendous difficulty of reproducing complex movements such as walking or dancing, robots designed for entertainment are 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. 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 robotics, 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, we devised an experiment that uses marionette puppetry 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 themselves, 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 valley. We have found that indirectly automating a performing object, as a puppeteer animates a marionette, is a useful method for investigating the dynamic, interactive processes between the puppeteer and the puppet, and the unique aesthetics of movement that result from this interaction.

The Pygmalion myth—the story of the Greek sculptor who carves an ivory statue of a woman which is 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 and 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, 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 segments from the play and demonstrated the user-interface. Visitors were able to interact with the system, designing marionette choreography in real-time by using software that translates their movements into choreographic sequences for marionettes. Presently, Disney Research is conducting parallel experiments using this technology. 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 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 REPRODUTION

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 in 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 clockwork mechanisms. Animatronic figures, such as Disneyland's Abe Lincoln android and the Jack Sparrow figure on the *Pirates of the Caribbean* ride, are automata that are powered electronically and rely on hydraulics and individual motorized joints to move. They operate according to a predetermined program run by a computer which 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 could play twelve different melodies and Jaquet-Droz's *Draftsman* could sketch four different drawings— their range of expression is limited to a pre-determined set of behaviors.

Tele-operated figures are mechanical figures in the shapes of humans, animals, or other fanciful creatures that are 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 pre-programmed expressions and gestures. However, because these objects are operated by a human agent, they can often appear to be more interactive and expressive than their automated counterparts. A tele-operated figure has more in common with traditional puppetry because it relies on vocal and motor sources of power which are outside of it, and which are not its own attributes.[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 through the agency of human "puppeteers" off-stage.

Because of the constraints of live-performance, such as the uncertainty introduced by the presence of other 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 directed 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 because, unlike in real life, the interactions are scripted and human agents offstage can respond immediately to changing circumstances. 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) in favor of more stable and repeatable motions which do not require 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 motion control challenges, weight, and safety concerns makes it difficult to create compelling theatrical illusions.

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 space. In rod puppetry, the puppeteer provides stability for the puppet, and the expressive movement is 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 the animatronic figures at Disneyland), but because there is no human intention or artistry powering the motions, the resulting movements looks mechanical or rigid. We might call this a kinematic version of the *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 are habitually perceived as soul-less? 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 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 for operating them, make it difficult to replicate precisely human and animal motions. Because marionettes are controlled by strings (rather than 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 (rather than directly powering the individual motions of the puppet), 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 human 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 that cannot precisely reproduce human locomotion. For engineers, this process 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, but they have far less than a human body: depending on the number of strings, a typical marionette has between 45-60 degrees of freedom, while a healthy human has upwards of 1,000. And yet, in the hands of a skilled puppeteer, these figures are capable of a wide range of expressive and nimble choreography that emulates human movement. Rather than replicate the mechanical processes of a human walking, a marionette *indicates* walking, using the ground only as reference point, and not as a physical constraint. As Kleist observed, unlike humans, 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: 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

We have established that marionettes are technological tools capable of a wide range of expressive gestures which are dynamic—their movements are controlled by forces outside of the object. In our initial conversations with Ludwig, we learned of an approach to 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 motion for the spectator. To translate this approach into engineering terms, our first task was to describe the puppeteer's three-step process in computational terms. To do this, we had to model mathematically what a puppeteer does intuitively.

Ludwig described how marionette choreography is divided into small units of motion, each lasting a specific amount of time (Egerstedt *et al*. 2007). 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 (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 approach choreography. For the *Pygmalion Project*, we used two interdependent approaches: we created a software program called *trep* (sic) that translates human choreography into puppet choreography (i.e. mathematically transforming human motion into feasible puppet motion), and we designed a robotic platform for controlling the marionettes. The software programs the robots to "perform" a marionette play, essentially enabling the robotic controller to assume the role of a human puppeteer. Unlike traditional puppetry, however, an engineer cannot rely on a human agent to interpret the "script." In a fully-automated system, the performing object (marionette) and its robotic controllers remain passive and mechanical; therefore, the engineer 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. A human puppeteer operating a marionette relies on intuition and what Chris Carroll calls "a vast unconscious vocabulary of movements": they always know where the audience is seated, and are continually aware of the positions of their left and right hand at any given moment (Carroll 2011: 73). One of the most challenging parts of the experiment was coordinating and controlling the movement and efforts of the robotic controllers in such a way that approximates this intuition—something human puppeteers do instinctively.

We devised the choreography with professional dancers— a wholly different approach from that of a traditional puppeteer, but one necessary to generate a set of data points to act as a mathematical "script" to start with. First, we encouraged them 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 (Fig 1). This system uses infrared sensors to track individual points attached to the dancer's body and 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 translate the human motion into abstracted marionette motion. The *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 two-dimensional imaging (Figure 2). These "inputs" are then used to program robotic controllers which, like a human puppeteer, control the marionette by pulling on its strings from above. By indirectly operating the puppet, we are able to create different type of automated motion for the puppet that is suggestive, without precisely replicating the physical processes involved.

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. Again, because marionettes have fewer degrees of freedom than humans, their movements are already abstracted. Since we are interested in exploring the mechanics of movement—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 a stage comprised of two pivoting mechanical arms equipped with individual motors to power winches for operating 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 in traditional puppetry. In some respects, this early design was as limited as the heavily stabilized systems we were trying to avoid; robotic arms cannot approximate the fluid, dexterous, and wide range of motion of a human puppeteer. Around this time, engineers at Disney Research and graduate students involved in this project developed a more flexible system for controlling marionettes, one which would lead to the prototype for the *Pygmalion Project*. They first experimented with the design of a 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.

We replaced the robotic arms of the original design with a custom-designed metal chassis equipped with individual winches that operate the strings, and separate motors to drive around the stage (Figure 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 both the robots and the puppets they control.

The robots have 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 (Schultz *et al*. 2012) Currently, a single human-shaped marionette is controlled by three robots, and it is attached using six strings: two head strings, left forearm, right forearm, left knee, and right knee.

We approached the task of imitating human movement from two directions: automated motion and tele-operated motion. For automated motion, we used the *trep* software to replicate as closely as possible the original choreography recorded from the human dancers.[8] Working with short choreographic phrases, we learned which motions are the most aesthetically interesting and stable (or unstable). Controlling the natural swing of the marionette in between movement phrases is a particular challenge. The second approach is 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 quite 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 their movements being imitated by the marionette. The Kinect has proven a useful tool for designing animations in 2D and virtual environments, and our system demonstrates how it can be used to animate motion for inanimate objects in the physical world.

Currently, engineers at Disney and Northwestern are experimenting with variations of the automated marionette system. Disney is 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 the lab at Northwestern, we continue to develop the Pygmalion choreography using only the robotic controllers and are currently focusing on grouping together longer choreographic phrases.

PUPPETRY AND FUTURE ENTERTAINMENT ROBOTS

In his essay, Kleist recounts a story of a young man who, despite his many efforts to precisely reproduce a motion, is unable to recapture the grace of the original pose: the youth is constrained by his own self-consciousness. For animatronics, it is the lack of human consciousness that prevents the robotic actors from appearing lively or graceful. If, as Kleist suggests, human dancers can learn from puppets how to free themselves in order to recapture grace, then engineers might also learn from puppets how to create more graceful and lively automated figures.

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 Handspring Puppet Company's *Warhorse*, spectators witness how skillfully three puppeteers can instinctively and silently interact with one another when controlling a single puppet, collaboratively creating the illusion of life through the artful manipulation of an inanimate object. However, designing automated systems that operate equally elegantly with a comparable level of collaboration and intuition remains a difficult task. We have outlined how a puppet-centered approach might address these challenges by creating more dynamic automated motion. Puppetry is not only a metaphor for mechanical motion, but also a useful method for investigating the dynamics of movement and human intuition.

The presence of autonomous robots onstage does not eliminate the need for human performers any more than industrial robots have eliminated the need for human labor, or than a live horse challenges a puppet-horse's legitimacy onstage. Rather, just as industrial robots changed the type of work that humans could do and empowered them to do other things (Friedman 2012), and just as puppets continue to artfully imitate the human condition, entertainment robots will create new types of performances and theatrical illusions. The presence of autonomous machines on theatre stages invites us to consider how these technologies are shaping the future of live performance.

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[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, S. (1992).

[3] H. Jurkowski 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" (Jurkowski 1985:55).

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[4] Kang, M. (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] According to 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 *trep* simulation and the corresponding marionette motions are available at HTTP: < 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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