The Robot Etudes

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***Abstract*— In spring of 2010, architecture and engineering students at the University of Pennsylvania were teamed together to create artistic mechatronic robotic devices. The context for their creations was Shakespeare's *A Midsummer Night's Dream*. This became a joint effort between professors from Mechanical Engineering and Architecture and a director from a professional theater troupe instructing a group of students to develop a performance performed by the Pig Iron Theatre Troupe at the Annenberg Center called *The Robot Etudes*. Whereas robots have been used in theater before and artistic directors have instructed technicians to develop special effects robots, developing robotic elements specifically for theater with a diverse set of creative innovators is new. This paper focuses on the process by which the play was formed and the successes and struggles in forming a cooperative experiment between three very different disciplines.**

I. INTRODUCTION

Robots have been introduced among live performers in the realm of dance as well as theatre often with robots either as the central piece of the action [1], [2] or as side props. In the former case, the impact of those events has often been on the uniqueness or curiosity of having a "robot", electro-mechanical element, where one is not expected. Often the juxtaposition of mechanical with biological on a stage is interesting and sometimes jarring. However, once the audience has accepted this juxtaposition, it would be interesting to explore deeper interactions. Part of this work intends to explore those issues.

The second major contribution of this work is the examination of the interaction of three disparate disciplines: architecture, theater and engineering. In some cases, it is possible to have individuals who are multi-talented or have experiences in multiple domains. Such people can implement and translate as necessary among the disciplines but this production had experts in their respective domains that needed to learn from others.

Engineers are naturally concerned with the technical requirements of making robots work and making them move efficiently. Architects are trained to think about space, scale, and enclosures that create an aesthetic environment much like a theater set. The design contribution from these non-theater fields is more likely to generate new concepts than using set-design professionals. Both engineers and architects are required to employ design strategies, but the evaluating criteria is not always shared. What engineers may call successful design in expediency, efficiency and performance may not coincide with the architectural design consideration of beauty, and sensory pleasure. Likewise what the actors may desire in terms of performance or reliability from the robot may not be technically feasible. The experiment for all groups was to create an enhanced theater experience that would be greater than a sum of its parts

Shakespeare's *A Midsummer Night's Dream* was chosen as the focus of the play, fitting within a series of explorations into this play by Pig Iron Theater. The play is about four young lovers and a group of amateur actors, who are manipulated by fairies who inhabit a *magical forest*. Rather than simply implementing the play with robots as actors or as set pieces, the focus was on the "magical forest" in which much of the play takes place. This way the non-human nature of electro-mechanical components could fit well theatrically and are used to bring about the themes of love and manipulated love.

A. Previous Work

In this work we are interested in the interaction between human and robot actors so we describe some of the previous work done in which robots shared the stage with human actors, as opposed to a performance by robots only.

The first instance of using robotic technology among dancers is described in Margo Apostolo's work on Robot Choreography [3]. This work concerned itself mainly with how to make robot arms move in an aesthetically graceful way and also brings to our attention the danger of using large robot arms that can easily injure humans. Nonetheless, robot arms as tall as 2.5 meters played parts in *Invisible Cities (a robot ballet)*, *Mars Suite*, *Orbital Landing* and *Sunset on Mars* [4].

In a play called *Robottens Anatomi* several robots including a modular robot called Odin were used [5]. This play consisted of a series of interviews of scientists including real robotics researchers talking about their research. They demonstrate what their robots can do. Later they bring in an actor who plays the part of a very sophisticated robot doing similar things. They blur the line between what is unbelievable and believable.

The insertion of robots into a complete theatre play is described in [6]. Four quad rotors and six toy helicopters were tele-operated and paired with human actors on the stage. This work also concidentally involved Shakespeare's *A Midsummer Night's Dream*. The authors discuss the importance of improvisation during the play as a reaction to a crash or errant behavior of the robots and describe a preliminary taxonomy to create affect exchanges between robots and human groups.

In *Cymbeline* a collaboration was created between robotics researchers at CMU and a theater troupe in Pittsburgh. Printers were used as an autonomous technology to enable interaction between the audience and the actors [7]. While not full-blown characters, these machines acted as props in the play which allowed the audience to participate in the play.

While these and other theatrical implementations of robots have used robots created for other purposes (industrial robot arms or off-the-shelf equipment), building robotic devices from scratch explicitly for the theater allows more creative freedom in the delivery which is the focus of this paper. It is interesting to make the distinction between technology driven artistic content and artistic driven technology content. Whereas the former characterizes the bulk of the work listed in this section, the latter is characteristic of high budget plays and movies where special effects technologies have been developed for commercial purposes. The work described here sits uniquely in the middle of the two directions. Machover has been exploring similar approaches [8], however we also bring a unique collaboration. The technology content, the design content and the theater content were co-developed. Engineers presented what technologies were possible. Architects cast the technologies in interesting visual ways. The theater directors determined how things could be used theatrically.

In a project called Robot250 collaboration between very different disciplines such as the arts and engineering have been described in [9] in which non-experts were taught technology through workshops. Besides describing the human robot interaction and artistic outcomes, this paper also describes a workflow which we found particularly effective in getting the arts and engineering disciplines to collaborate closely together toward the final performance.

II. DEVELOPMENT PROCESS

The three distinct groups are described in more detail here.

- There were eleven **engineering students**. They had all taken an introduction to mechatronics course previously, but had little design arts background. They were in the mechanical, electrical or robotics masters program at the University of Pennsylvania.
- There were ten **architecture students** also masters students, mostly in their second year of their work - which included a separate studio course and had significant design arts background, but no mechanical or electrical engineering.
- The **theater troupe** was *Pig Iron Theater Company* [10], an award winning group based in Philadelphia that has been developing original work for 15 years touring the US and Europe. This group included a director, actors, a stage manager as well as sound, lighting, stage and costume designers. This troupe has many years of experience in creating new ways of delivering theater, but had little experience with robotic technologies.

A. Goals

All three groups had the shared goal of a successful theater performance. However, the students also had a learning goal. Ideally, the students from the two different backgrounds would learn from the other discipline to the effect of a greater level of production. This entailed not only learning to implement advanced mechatronics, but also to design a synthesis of mechatronic and theatrical elements. Traditionally there is little cross-learning between the design disciplines and engineering, and this theater production proved an ideal setting to move the coursework from theoretical proposals to realized, working prototypes. Realistically, the engineering students would be exposed to the artistic design aspects, but have less to contribute than the architecture students, just as the architecture students would have less to contribute to the technical engineering but more to the design sensibilities. All the while, the theater troupes' first priority was the performance.

The conventional theater process of working from a script with a director who commands all actions and aspects of the show would not work well with the uncertain/unreliable nature of student-built devices. In many ways, the joining of the students faculty and theater personnel was an experiment in learning about the cultures involved. So matching the expectations and desires of what could be achieved mechatronically and artistically by the students required an extremely flexible theatric process.

The Pig Iron Theater group has a unique dramatic process that is in part based on iterative improvisation that relies on the director for an overarching goal, but with weaker control of the actors who improvise lines and actions based on high level instructions of the director. As such the group (actors and director) jointly develop scenes based on what works. Incorporating varied artistic mechatronic elements were then developed into scenes based on what the machines looked like.

B. Process

Architecture and engineering students were paired together in creative teams. After a "bootcamp" session in which both sides learned some fundamentals about the other side, the teams were tasked with creating some kind of mechatronic device that would fit the basic theme of the magical forest.

In the iterative development process the script was created in parallel with the design of the robots. It included weekly improvisation sessions involving everyone: director, actors, architects and mechatronics engineers, in which a scene was continuously prototyped and refined. A typical session would involve partial creations by the architects and engineering students in which the actors and director would see what kind of scene could be made involving those devices. As such, the theater personnel had to do some projection to imagine what the system would look like when finished, but would also set direction for where the development of those devices should go based on the outcome of these sessions.

This was extremely demanding on engineers as design requirements were constantly changing and a willingness to discard and redesign was necessary as the script evolved every week. The iterative approach may seem unstructured, but was particularly useful in finding the hidden assumptions early on in the process. The theater personnel could much earlier converge on what was technically feasible and the engineers could see with their own eyes what would work on stage. Furthermore, this process emphasized close collaboration of the architects, engineers and actors in the early stages of the project rather than subdividing tasks and having the three disciplines working separately and combining works at the very end.

In the first half of the development process, the participants were encouraged to collaborate and exchange roles. For example, the engineers could give suggestions on the acting, the architects thought about the engineering. Directions were set very loosely. After the different backgrounds gained an understanding of each other and the deadline nearing, there was more focus on one's individual discipline again. In the final portions of the development process efficiency demanded a client-based model, where the theater troupe was the client and the architects and engineers provided the service so directions were more concrete.

The success of this iterative approach relies on the experience and talent of the theater troupe. In this case the Pig Iron Theater has over a decade of this experience developing this method of theatric production in which they have won several awards and have even started a school [11] to teach other theater artists this technique.

III. THE SHOW

A. Theme

An interesting challenge for any production of *A Midsummer Night's Dream* is how to represent the forest on stage. The magical forest was thus a natural place to focus the application of untraditional technologies. This helped to set one of the major themes of representing the interplay of the two worlds of dreams and reality.

The second theme which was extracted from Shakespeare's play is that of love. Manipulated love was particularly interesting to the theatre directors in the context of robots and the control of them (or lack thereof). For example, in our etudes a man and a woman meet in a dog park and use their robotic dogs as an ice breaker. A magic flower can manipulate men to fall in love by wrapping its petals around a man's head or in another scene shooting a potion like a bow and arrow.

B. Etudes

This section provides a list and brief description of the human and robot actors. We describe the mechatronics and then the on stage interactions between the human and robot characters.

1) FIREFLIES: *Fairies appear as small lights that flicker as sounds are made.* Small devices consist of super-bright LEDs are driven by an op-amp, taking input from an electret microphone and powered by a watch battery. The unit cost of a firefly device is $1.76 enabling the creation of many. The actors hold these small devices close to their mouths. As the actors make sounds the devices light up in proportion to volume illuminating the inside of their mouth.

On stage: The stage is completely dark. The fairies are appearing and disappearing as they laugh and make forest creature noises. All the fairies exit except for two. The two are each lit up back and forth by the rings as they argue with each other.

2) GARDENERS: *The magic forest has caretakers.*

On stage: Two human actors enter dressed as gardeners carrying flash lights. Another gardener enters with pruning hedges uncovering gourds (Fig. 1b) and a woman who apparently fell asleep in the forest without being aware of the gardeners. It is made clear that it is early morning and the gardeners are the ones tasked with maintaining the magical forest. They are reminiscent of the mechanical characters in *A Midsummer Night's Dream*.

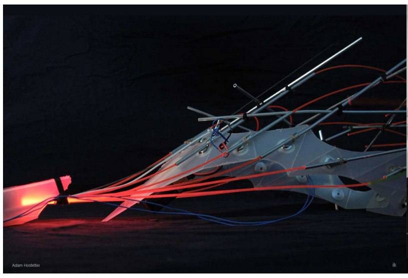
3) SQUID CROWN: *A fairy wears a crown of multicolored fiber optic sideglow cables.* On this head piece (Fig. 1a), glowing optic cables transform from a regal headdress into a mosquito-like beak by extending the cables forward which end in a bright bulb hanging in front of the actor's face like a nose. The placement of the bulb is adjusted manually by extending or shortening the cables from the back of the head.

On stage: A fairy wearing all black enters the dark stage wearing the crown. The actor transforms the crown into the mosquito-like beak, hovers around the woman from the previous scene in an insect-like fashion. The woman is for the most part unaware of the fairy but flicks the actor away when he gets too close.

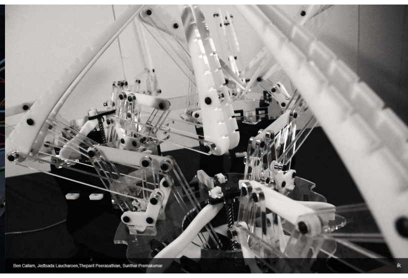
4) WINGS: *A winged robotic creature from the forest is in disrepair.* Human scale wings (Fig. 1d) are made up of a five degree of freedom (DOF) linkage: one prismatic joint for vertical movement of the full wing structure and two revolute joints for each wing to open or close the wings. A strain sensor is attached to a belt that goes around the actresses midsection which can sense the inhaling and exhaling of her breath. There are two modes for the motion of the wings. In one a control loop is closed such that the wings move up and down as well as open and close in proportion to how much the woman breathes in and out. In the second mode a staccato robotic like movement could be induced by contact switches in a glove input device. The first mode is fluid and lifelike while the second mode conveys a sense of malfunction.

On stage: Two gardeners enter and work on repairing the equipment (that is the woman with wings) whilst arguing with each other. The woman malfunctions and grabs one of the gardeners.

5) Dog Park: New social encounters occur with robot pet owners. One robot dog (Fig. 1e) is a toy RC car dressed up with a lamp shade, the other a remote controlled two-wheeled unicycle robot. Both are tele-operated and drive around bumping into objects on the stage. In autonomous mode (not used during the play), fiducial markers are placed on the robot and tracked using an overhead camera. Autonomous behaviors control the robots to approach or run away from other fiducials that the audience can play with.

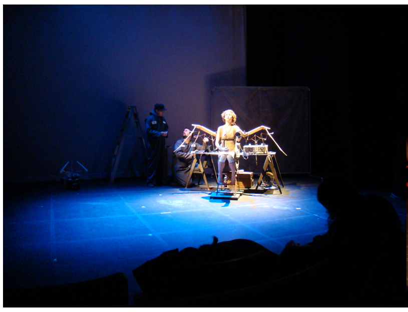


(a) Squid Crown



(b) Musical Gourds

(c) Blades of Grass



(d) Wings

(e) Dog Park

(f) Caterpillar

(g) Poofy QTip

(h) Flower

(i) Lullabye

Fig. 1: Characters

On stage: A man and a woman enter with their robot dogs and stand at opposite ends of the stage. A stereotypical scenario of two people meeting at a dog park ensues. The robot dogs run around the stage. The man and woman shyly make small talk about the weather and each other's dogs. The dogs run into each other and the man and woman rush in to pull them apart. Now standing closer to each other they make more small talk and decide to go for a drink. Man and woman exit stage right, and gardeners strike the robots from the stage.

6) MUSICAL GOURDS: *Robotic plants can open and close and emit unique rhythmic sounds.* Each plant (Fig. 1b) has one DOF consisting of four petals which are linked mechanical four bar linkages. As they open and close, the steppers driving the four bar linkages make a loud noise. This was to the dismay of the engineers when the prototype was first presented. Unexpectedly, the actors loved this sound and opted to amplify it with a contact microphone, transforming the gourds into musical instruments.

On stage: Spotlights turn on highlighting the gourds. The gardeners, turn on the gourds one by one, sit down and start jamming with each other using the plants of the magical forest as musical instruments.

7) FLOWER: *A large flower that has the power to cause people to fall in love.* The flower (Fig. 1h) has large petals that are constructed of a series of parallel flat slices that subtly form the shape of a human face in bas relief within each compliant petal. The petals curl in to be closed or opened using a motorized pulley with a tendon to each flower petal. The petals can also be released suddenly from a curled state which causes them to spring back much like a bow releases an arrow. In addition, the flower could be actuated in a panning motion to look around the stage. The flower is reminiscent of the love potion which like in Shakespeare's play had the power to make someone fall in love with the first person they see after they awaken.

On stage: The flower tracks one of the human characters as he walks in the forest. This tracking draws his attention so he moves in to examine the flower closer and closer until his head is inside the flower as the petals slowly closed. Once the flower releases the character's head it becomes clear he is now in love with the other actress on stage.

8) BLADES OF GRASS: *Tall grass moves rythmically with a couple.* The field (Fig: 1c) consists of one meter tall grass blades that bend using shape memory alloy (SMA) actuators. The blades of grass can be manually actuated or programmed to pulse and sway with a regular pattern that can be modified with sensor input. (For the stage show only the manual option was used).

On stage: Two lovers dance in between the blades of grass as they bend back and forth.

9) POOFY QTIP: *Love blooms between a tall blue puffy plant and a gardener.* The animated character (Fig. 1g) here is a six-foot tall, three segment arm spring loaded at each joint, actuated from the base. The arm has a tendon based two DOF mechanism so the arm can be controlled to bend and point in any direction. There are ultrasonic sensors around the base of the plant that enable a behavior where the plant bends towards someone if they approach. (This latter behavior was only used after the proper).

On stage: A gardener checks up on the Poofy QTip. She (we will assume a gender here) is in love with one of the gardeners which becomes obvious when she bends over and gets a little too close for the gardener's comfort. She gets denied by the gardener who walks away. The gardener gets struck by the FLOWER. When the gardener awakens, he is in love with the Qtip. "The course of true love never did run smooth."

10) CATERPILLAR: *A glowing pulsing creature evokes motherly feelings from the gardeners.* A caterpillar (Fig: 1i) made of dozens of linkages and white LEDs pulsates with a lub-dub rhythmic pattern. The light on this robot is teleoperated via wireless. GRASP's modular robot called CKBot [12] makes a cameo appearance in a caterpillar configuration.

On stage: A gardener shows the other gardeners the glowing caterpillar and they start singing a lullabye to it. Several snake-like modular robots enter the stage and the other gardeners pick them up as a family of magical creatures which they sing to sleep.

Quotes from the Shakespeare play are piped in from a blatantly computer synthesized voice reminding the audience, that if they were upset by anything in the play, this could be mitigated by the idea that this was all just a dream.

Lights out.

The audience is invited to come down and interact with the mechatronic devices now put in autonomous mode.

IV. RESULTS

A. Etudes

It was hoped that the *Wings* piece would have a particularly interesting interaction between human and robot. In this case the human actress - pretending to be a robot - did not speak and in fact limited any appearance of outward emotions. The motion of the three DOF wings would convey the actresses emotions. Spreading out, rising gracefully, short fast fluttering or flapping intensely could convey her emotional state. For the show the storyline veered towards the anthropomorphized winged robot - needing repair as the workmen discuss the objects condition. It worked well in evoking a loneliness and yearning of the winged actress, though the piece needed to rely on lighting and music to evoke the proper emotions rather than just the mechatronic wings.

The least mechatronically complex etude piece was the *Dog Park*. This used one toy RC car and one teleoperated mobile robot, both dressed up in odd ways. One early proposal was to have entirely autonomous robots performing some behavior through overhead cameras utilizing an open source computer vision package NyARToolkit [13], which is a C++ port from ARToolkit [14] for tracking fiducials and OpenCV [15] for interfacing with the camera. The behaviors would be limited to some known set of boundaries from which the actors could interact. However, technical reliability became an issue as the show time approached and complete human teleoperated control was utilized for the show. This teleoperation by an actor turned out critical to the success as the motion of the "dogs" was what made them interesting theatrically. Even though the expressiveness of an object moving in SO(2) is limited, several audience members considered it one of the more thought provoking pieces. That the actors on the stage never once treated their "robot dogs" as anything other than their pets brought up several of the more contemporary issues of robot ethics as people start to develop new relationships with mechanical systems [16]. After the show, the engineers were able to show the technical aspects of behavior based motions through overhead machine vision.

One of the most comedically successful pieces was the *Poofy QTip*. This piece was an example of great acting, a uniquely clever visual implementation and a simple yet compelling and reliable mechanism that provided a smooth organic two DOF bending motion. The absurdness of a large blue feathery plant-like object falling in love with a person is what makes it interesting and is in large part due to the conceptual design of the architects. The mechatronic elements which control its motion shows the audience that this is something more than a giant blue QTip or a big blue plant. And it is the acting that conveys the story that indeed there are emotions involved here.

B. Audience Reaction

As with most artistic endeavors it is difficult to determine quantitative measures of success though most people interviewed considered the show an outstanding success. There was a single showing that was oversold with approximately 200 people in attendance. The audience remained for nearly an hour after the show to talk with the actors, engineers and architects and observe the technical elements in autonomous modes. Anecdotally, one of the school's Deans raved about the show and was trying to set up a second showing.

C. Collaborative Learning

There was much to be learned from this collaborative exercise.

For the students of architecture, the greatest learning was in making active, moving environments. Much of architecture as a curriculum is in static, inert building design - the opportunity to propose and implement mechatronics was a unique experience and led to greater discussion of our architecture as an active environment. Furthermore, the collaboration among engineers and theater people left a strong impression.

Similarly the engineers learned about the design and theater culture while also learning about shape memory alloy, machine vision and wireless control. The amount of mechatronics learned was less than a class focused solely on mechatronics as a larger percentage of time had to be devoted to the theater development process. The concept of "design sensibilities" is often foreign to engineers focused on function rather than appearance.

Overall the experience was valued by all involved. In large part this was due to experiences from working closely with areas so different from individual's normal interaction. It is clear from looking at the end results that many of the best aspects of each etude resulted from contributions from each field; the interesting visual appeal in each object was clearly delivered by the architecture students; the mechatronic motion and control by the engineers, the delightful story telling and evocative acting by the theater personnel.

Yet not everything went smoothly. There were plenty of clashes and disappointing interactions amongst the three groups. Even with the knowledge that student work is not as dependable as professional work, the theater expectations on the technology had to be scaled back from initial concepts to be sure that the show yielded a baseline performance. The engineering student expectations on their architecture student teammates' participation needed to be lowered as the class was considered a seminar course which has lower priority than the studio course they took concurrently. The architecture students found it frustrating that their creative input often did not match with what the directors would find theatrically viable. In many ways, it is these differences in expectations and opinions where the learning about the different cultures occurred.

One point of contention was autonomy. While it would be the most interesting from a technical point of view, from a theatrical point of view, it doesn't matter how the pieces are truly controlled to move, as long as they move the way they should and the audience believes what is intended. In the end a compromise was reached where after the etudes were performed the audience could interact with the devices which would react autonomously.

For future student collaborations of this nature, our experience we recommend the following.

- Strike a balance between learning other disciplines and playing to the strengths of each member. We made the mistake of too much cross-training.
- Be sure priorities and time commitment expectations are set early (as they often vary widely between disciplines).
- Reliable hardware is critical. This makes it difficult (but not impossible - as we have shown) to use student creations in one semester.
- Creative direction is something that architects normally control. For theater to run efficiently, often a single director has that control. Setting expectations appropriately between the two is a good idea.

V. CONCLUSION

The success of the show was an indication that this approach to robot and art interaction can work. If run for the first time among groups unfamiliar with other the disciplines, much patience, understanding and flexibility is required. However, the end result often validates the hard work.

Although the shared interdisciplinary experience was a critical learning element, student teams could have reached a higher level of production had they had more familiarity and more accurate expectations. Many proposals of potential were left off the stage due to time constraints and requirements of remote control. However, the amount of design work and the levels of resolution was very good for a single semester of work and planning.

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