THE CONDUCTOR

An investigation into accessible, effective and affordable animatronics for theatre

By

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Introduction

Animatronic characters in theatre are underutilized because of the common fallacy that creating both an effective and affordable animatronic character is out of reach for most independent theatre companies. I believe this is not the case, and with my dissertation project I intended to prove my hypothesis by designing and building an animatronic character for a theatrical performance. My goal was to create an animatronic at a fraction of the price of most systems on the market that was still effective as a character. In order to prove this concept, I have written a short one-act play with a robot as the main character. The character would be powered and puppeteered wirelessly to allow it to seem automated, enhancing the audience's perception of the character as an individual rather than a puppet. There have been many examples of animatronic characters in theatre, but there have been few that come close to resembling an autonomous, believable character while remaining affordable and accessible.

The play follows a robot that was unfulfilled with its original purpose and instead chooses to become the conductor of a rural train station. The two other characters, a human and a fox, view this station as an island away from their normal lives. Over the course of the play, we follow the three characters, their burgeoning friendships, and the changes they undergo from these relationships. The Conductor character is the animatronic, the fox is a traditional hand puppet and the human is an actor/actress. By limiting myself in terms of articulation and speech, I developed methods of communication that grew out of movement and a physical cultural association. I have tapped into the inherent ability of puppets to be a canvas for the actors and audience to project their own emotions onto. Puppetry gives life to the inanimate and if the audience is to believe the Conductor is aware of itself, its feelings can be translated by the puppeteer

I built the robot character with methods that anyone with access to a collection of personal tools and community workshops such as makerspaces can utilize. This project acts as a starting point for any those who wish to include animatronic characters in their work but are discouraged by the perceived expense of building animatronics. During this project I researched, identified and built using affordable technology like Arduino, custom circuitry and easily sourced mechanical parts. With this character, I hope to demonstrate that animatronics can not only be used in high budget film but also within the theatre world, no matter the level of the production.

Animatronics and robots in theatre

The theatre is no stranger to robotic characters, with one of the first in 1920 in Karel Capek's *R.U.R. (Rossumovi Univerzální Roboti (Rossum's Universal Robots))* (Capek, "R.U.R.", 2001). In addition to its extreme popularity after its first production in 1921, this play coined the word "robot". The play tells the story of robots being created in a factory that uses a semi-organic matter to create something we would now call clones. During the course of the play, the robots integrate into human society, although over time the robots rebel and exterminate the human race. Even though the interpretation of robot then is different we can see still that humans still treat the idea of self-aware robots the same way, with disrespect and ultimately fear. The play is cast and staged with humans in costume and makeup performing as the robots. Other uses of robotics in theatre include the work of Alan Ayckbourn who frequently uses the idea of AI and in his plays, including *Henceforward...* (Ayckbourn, Henceforward..., 1985) and *Comic Potential* (Ayckbourn, Comic Potential, 2000) . Despite the wealth of works written about robots and robotic themes, these productions are almost exclusively performed with human actors.

Animatronics have only recently taken centre stage as fully-fledged characters within plays. In 2006, Les Freres Theatre in New York stage *Heddatron* (Meriwether, 2006), which is considered the first play with actual robots playing robotic characters in a professional capacity. The play is a reworking of Ibsen's *Hedda Gabler,* in which a pregnant housewife is abducted by robots and forced to perform *Hedda Gabler* religiously. Even though this play sports a sizable cast of three robots,[1] it is mentioned in the set direction that if functioning robots are not available then they can be substituted with "…*something on wheels with recorded dialogue.*" The intelligence of the robot, however slight, is what conveys the robot's character, which could be easily shown through the physical construction and puppeteered control. This stage instruction demonstrates that the main function of the robots in *Heddatron* is to convey

1 See this video for an example of the production, https://vimeo.com/48961498.

their character almost exclusively through dialogue, and not through their preprogramming or puppeteering. By negating the assumed "intelligence" of a robot by making it apparent that they are not autonomous (or perceived to be autonomous) strips the character of any individuality.

In Japan, Oriza Hirata, the leader of theatre company Seinendan has also devised plays using robotics. His first play including robots, *I, Worker* (2008), featured two robot characters that were programmed to recognized their counterpart's speech and answer accordingly, in addition to preprogrammed movements. The play tells the story of a father struggling with the loss of his child and his relationship with an assistant robot who has lost the will to work. The staging is simplistic, with black walls and a small table in the centre of the room. The robots are humanoid in their looks but not in their movement, which is slow and overtly precise. Their speech recognition also creates delays in their responses, though this aspect of the robots becomes part of their character, showing their sarcasm with great comedic effect. Though no precise details of their functionality have been released publicly, the play is only thirty minutes long, indicating probable issues with the capability of the batteries in the unit and the limitations of the robot's expression. A few years after *I, Worker,* Hirata devised his second play featuring robotics. *Sayonara* (2012) was written for the event Shinsai: Theaters for Japan. The event was a relief effort in Japan to help the communities around theatre who were affected by the March 2011 earthquake and the resulting nuclear crisis in and around Fukushima. *Sayonara* tells the story of an android built to be a companion and read poems to those who suffered after the disaster. Throughout the play, the mechanics of the android also begin to deteriorate, and the meaning of life and death for both humans and robots is called into question. The android is built to resemble a life-like woman[2] and does tread very closely to the uncanny valley. The uncanny valley is a hypothesis that states that if a human replica is close to being a perfect copy but not quite, it will illicit eeriness and revulsion. Again, the precise details of the construction of the robot are not on public record, but visually it does seem to be tethered to a power source via a cable and does not move from a sitting position. The interaction is stilted, but very well realized. Both of these plays by Hirata were in collaboration with Dr. Hiroshi Ishiguro,

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2 See video for example of *Sayonara* https://www.youtube.com/watch?v=CWnnqObk1qM.

director of the Intelligent Robotics Laboratory at Osaka University, and both received critical acclaim and even toured as a double feature across Canada and the US in 2013 through a partnership with the Japan Foundation. These plays are great examples of robotics being integrated into the medium of theatre, but both are unrealistic solutions to any independent company. The research and development came from a world-renowned robotics lab which the director has close ties to. Without the funding and or support from researchers themselves these plays would not have come to fruition, an issue I believe can be circumvented by removing the researchers from the equation and enabling the creative team of the production instead.

The Creature Technology Company of Melbourne, Australia specialize in large scale animatronics for live performance. Their work includes arena shows for *Walking with Dinosaurs (2007), How to Train Tour Dragon (2012)* and most notably *King Kong* (2013). King Kong was a revival of a 1953 jazz musical of the same name. The central character in Kong was a six-metre tall animatronic and hand operated puppet[3]. Utilizing the skills of thirteen puppeteers, the giant gorilla came to life. While this was a truly fantastic spectacle, these giant puppets are also fantastically expensive and incredibly time-consuming to build. The King Kong musical took five years to finish preproduction, and the other shows by The Creature Technology Company had a similar time frame. Though the critical response for the design of the central character was positive, the production had difficulty moving to New York City due to other bureaucratic issues, and the production remains in production limbo. Even technically revolutionary animatronic systems have trouble seeing the light of day. This project was not just outstandingly expensive and time consuming but also suffered from the oddly unforeseen issue of Kong being too large as the Regent Theatre in Melbourne needed to be partially rebuilt to house the giant puppet.

In recent years' roboticists and theatre companies have been teaming up to tackle the problem of producing characters through robotics. Since 2005, Engineered Arts have been developing a system to

3 See video for example of King Kong https://vimeo.com/87822929

tackle this problem, resulting in the RoboThespian,[4]an android the size of an average human that is preprogrammed to perform defined movements and speak its lines. Though it is comprised of human limbs, it is unable to walk and must be given a at least a metre of space in all directions for the safety of the other actors and itself. The RoboThespian has been used in several plays but most notably *The Uncanny Valley (2013)*[5] and *Spillikin (2016)*[6]. In both productions, the RoboThespian is seated in a wheelchair and must be moved around stage very carefully. Due to its control systems, primarily pneumatic pistons, it must be permanently connected to an air compressor, which limits its mobility. The RoboThespian has a multitude of functionality, although the production necessarily must be tailored to meet its limitations. Additionally, the £50,000[7] price tag would surely turn any unfunded independent theatre company away.

Making compromises within a production to accommodate the functionality of a pre-built robot can cause a production to suffer. although there are productions that have embraced the specific qualities of pre-built systems and substituted some of the restrictions with components of their production. For example, the Gob Squad produced *My Square Lady* (Gob Squad, 2015) at the Komische Opera Berlin. This opera is based on *My Fair Lady,* but instead of trying to pass a lower-class woman as an upper-class lady, a robot, Myon, is trained how to be human. During the production, the robot is dismantled, sung to and walked around the stage[8]. The robot, built by Neurorobotics Research Laboratory at Beuth University of Applied Sciences in Berlin, was designed to sing and to be autonomous by learning during the production about the different roles of the characters involved. This is a great example of using our current level of technology to the best of its capability without trying to pass it off as something far more advanced. Like an actor who you can tell is “acting” an audience can spot technology they are familiar with and Myon I believe evades that recognition well. Even though it is effective, the production was

4 See link for information on Robothespian https://www.engineeredarts.co.uk/robothespian/
5 See for information of *The Uncanny Valley* http://www.uncannyvalleyplay.com/artist
6 See for article about *Spillikin* http://robohub.org/spillikin-a-robot-love-story-for-our-age-and-a-unique-campaign/
7 Article on Robothespian https://www.theguardian.com/technology/2014/aug/17/robothespian-engineered-arts-robot-human-behaviour
8 Video Trailer for *My Square Lady* https://www.youtube.com/watch?v=jWBN9627mSg
9 Video extract from *My Square Lady* https://www.youtube.com/watch?v=49rJMgJY1CU

shaped around Myon's features and that is just not an option for some productions.

I believe that to create a truly effective character that represents a future technology, you must build it to subvert the audience's expectations. A good example of this is the 2009 play *Robots* (Les Voyages Extraordinaires, 2009). This wordless play depicts the lonely life[9] of an inventor who lives with three robots. Throughout the play the robots interact with him and each other, as well as tread out a routine. The robots were devised and built by Autonomous Systems Lab of the Swiss Federal Institute of Technology in Lausanne (EPFL) and BlueBotics. They are semi-autonomous and have preprogrammed functions; they glide across the stage and are obviously built for predefined purposes. The dog robot sniffs the floor and eagerly greets its master. The butler robot attends to its master's needs throughout the day, following a schedule that is itself a reflection of the inventor's character. The inventor's final robot is a female android built as a companion, it moves with grace and is designed to be as human as possible. The programmed movement and effort to hide all the components and the form factor of the robots allow for a very convincing performance. Their movements even match the dance-like action of the human characters. The triumph of the character design lies in the robots capacity to surprise the audience by displaying a range of control and grace never seen before. Though once again this level of mechanical engineering and programming was provided by an external company that were building off pre-existing BlueBotics systems.

After seeing the current range of robots in theatre, I realized that the target of my project was not the audience itself but current and future practitioners of robotics in theatre. Currently, cost, length of development and accessibility are all major road blocks for a production team of any size to cross, and each of the aforementioned productions had trouble with at least one. *Heddatron* was reasonably well realized for that specific production but the accessibility of the engineering and programming got in the way. The RoboThespian could be programed easily through their in-house application, but the story suffers if the robot does not meet the requirements of the character, and for many, the price will out-budget any independent productions. Myon of *My Square Lady* is sophisticated and can "learn" its part,

9 Video extract from *Robots* https://www.youtube.com/watch?v=uBJsTSYhhlw

but it required the partnership of Gob Squad,a world-renowned robotics research lab. Even the effective characters in *Robots* could not be achievable without the help of François Junod[10], a master craftsmen of metal automata who designed and fabricated the motion of the companion robot. In terms of size, the scale of King Kong is something that most productions can only dream of building.

I believe that these road blocks can be easily overcome by introducing traditional theatre practitioners into the multi-disciplinary world of makerspaces and opensource platforms. A makerspace is an open space for fabrication that sports a myriad of tools, both hand and machine controlled. Makerspaces focus on building a community of likeminded individuals who help each other on projects. Not only are makerspaces a fantastic learning resource but they offer tools that are too expensive or large for the average user, such as CNCs, 3D printers, laser cutters and other industrial machining tools. Makerspaces can enable theatre companies of any level to build the robotics and network in a community of skills. The opensource platforms that are available range from free to use 3D models on the Thingiverse[11] to the massive code community of Github[12]. Opensource platforms encourage collaboration and sharing across and medium and when developing a robotic system, they are invaluable learning sources. We live in a technological literate world with communities built around collaboration and education that can be used to create effective and affordable animatronic systems.

The play

Story

The Conductor was inspired by an investigation into the possibility of a world shaped by the positive outcome of artificial intelligence. This story, examines the relationships between technology,

10 See for website of Francois Junod http://www.francoisjunod.com/
[11] Link for Thingiverse http://www.thingiverse.com/
[12] Link for Github https://github.com/

humanity and nature. We see a future in which AI is commonplace and in the far reaches of the country, away from major cities, there is a forgotten realm full of nature with islands of technology. A train station at the end of the line is one of these islands, and this train station is operated by our main character, the Conductor. The Conductor is a machine that was originally built for surveillance in a large city: its eye is always watching and its looks are unobtrusive. The Conductor found the city to be an overpowering and deeply morose place, in which humanity and AI became self-constrictive and ignorant to their individual needs. Like an ant colony, they piled up on top of each other, listening only to neighbors, superiors, while remaining blind to their own self-worth. The Conductor saw an opportunity to leave the city to operate a small barely used train station and jumped at the chance.

The play begins many years down the line, when a human from the city arrives at the station after being assigned to a position in the area. The human is initially taken aback by the hospitality of the Conductor, though they swiftly become friends as the days go by. During this time, a wild fox has stumbled onto the station from the surrounding forest. Like the human, the fox is at first cautious, but is soon fond friends with the Conductor. As time goes by, the human constantly obsesses over the life that they believe is right for them. The Conductor, however, knows that work and the city are not the only choice for them, and tries to convince the human of this fact, to no avail.

Research and inspiration

When developing my project, I considered adapting a text and attempting to build a robotic character for an already defined story. However, after my research into theatrical robotics, I knew that this would be too limiting, as I would have to base my design on an already written character's every needs or risk losing their main characteristics. I opted to instead write my own script. This way, I could make the play any length I wanted, and could limit any aspect of the stagecraft involved. Most importantly, I could design the animatronic do whatever was needed based on my set restrictions regarding affordability and accessibility in terms of creating the animatronic.

I have always been inspired by East Asian cinema and theatre, and saw this project as a perfect opportunity to explore techniques and devices for storytelling. I took great inspiration from Fei Mu and read a great deal about his approach to storytelling through every day characters and the mundanity of their lives which projects their true desire onto the screen (Fan, 2015). What I have tried to emulate is Fei Mu's ability to examine the real details of life and how it affects us as a society. He subverts the tropes of the traditional three act structure by simply presenting honest stories that are far more empathetic than other styles of storytelling. My play focuses on simplicity of the Conductors life and not the high stakes drama of the Human's relationship and career to evoke a shift of focus in the audience's perspective of their own lives.

Design and intention

The original inspiration for the story came from Japan, which gave me a very real and concrete location for the setting. My mother and I found ourselves lost in the countryside and happened across a train station at the end of the line that was manned by a train conductor. I was able to track down the exact train station in Google maps[13] and source photographs of the surrounding area. These were used as inspiration for the crew on the production. The lighting realistically represents the station lights and the lights within the Conductor's office, while also depicting the natural light. The set design uses simple cut outs of the Conductor's office, bench and tree with a white backdrop. The detail of the surroundings and the day and night horizon is projected onto the white backdrop. The sound design takes a very realistic approach by creating a soundscape imitating the natural sounds around the train station to immerse the audience in the environment. The music is arranged to blend traditional Japanese folk instruments and modern electronic instruments. This combination of styles has developed the location into a character itself. With no actual mention of Japan, mountain forests, or the time period I believe the audience will still feel grounded in the experience.

Development

The play started as a personal passion project last summer, but as the school year began, it swiftly

13Link to Google Maps view of from station https://goo.gl/maps/ct4V4TmR8742 accelerated into a group endeavor. After writing the first drafts of the script, I started getting initial feedback by giving my friends and colleagues drafts to read and critique. I also held read-through sessions to get a good understanding of their interpretations and see elements of the script in action. After writing out many revisions, I settled on a final draft, and was finally able to start gathering a crew to help with the production. I made an advertisement and circulated it around the university societies and groups, and after a short interview process, I decided on the following group to become my production team.

Erin Tomkins – Composer

Aiden O'Beirne – Sound Designer

Amelie Iselin – Stage Manager

Emma Sheldrick – Stage Designer

Mila Lawlor – Lighting Designer

Theo Mason Wood – Puppet Master

Karol Sielski – Conceptual Designer

Elsie Oakwood – Costume Designer

Johan Gelinder – Projection Designer

In January, our company was shortlisted as a finalist for the LET Award. The award is given out by the world renowned Les Enfants Terribles theatre company, with the goal of assisting young theatre companies by giving them a cash prize and a place at the Edinburgh Fringe Festival. Les Enfants Terribles specialize in puppetry, and when applying for the award, I felt they would appreciate what I was trying to achieve. While getting shortlisted was great news, we were still in the pre-production phase and only had a week to ready ourselves. During that week, we prepared a ten-minute section of the play and built the prototype of the Fox puppet as well as a hand-operated version of the Conductor. This process turned out to be an essential part of my project, as I was able to see the Conductor in action, interacting with the actors on stage, and get a better sense of the requirements of the animatronic.

Our LET Award show performance was well received, and although we did not win, which was expected, we gathered some fantastic feedback and essential experience. We were immersed in the world of progressive theatre; the next step was to audition actors for the remaining parts in the play. After a few rounds of auditions, the decision was made to bring in two very talented actors, both students at Goldsmiths College. The final cast list is as follows:

Delphine Bueche – Actor

July Zhiyan Yang – Actor

Cormac Joyce – Puppeteer

Now that the award preparations were complete, I could begin my first prototype for the robotic version of the Conductor. The feedback and critique from the rehearsals and award was invaluable and I will now always make a point of testing out a hand puppeteered version early in the process to get a concrete sense of how it lives in the play.

The first prototype

Paper

I started my design process in September 2016 by sketching up forms that could convey human emotions, but do not have humanoid features. This lead me to explore how to blend the human anatomy with geometric shapes. During this process, I wanted to make sure that I stayed away from anything defined so that I could easily drop orchange designs dramatically. This process was very important,as it would shape the building blocks of the engineering and of the character itself.

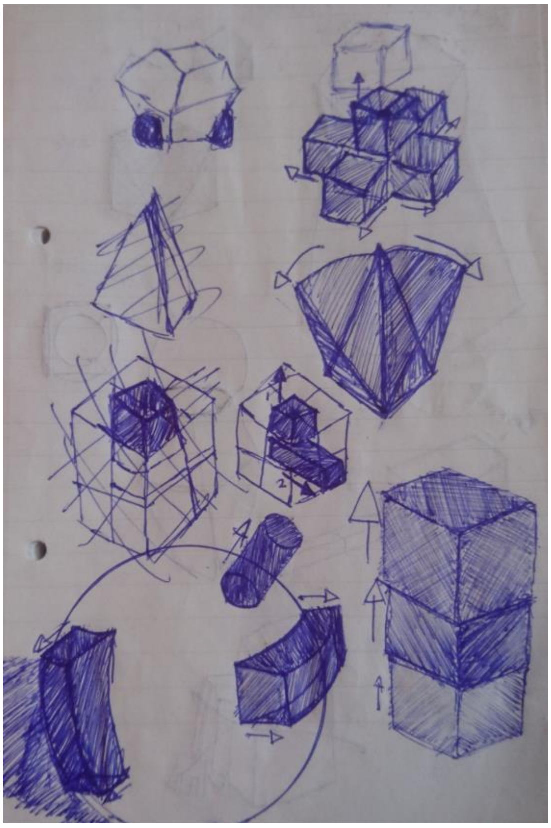

Figure 1

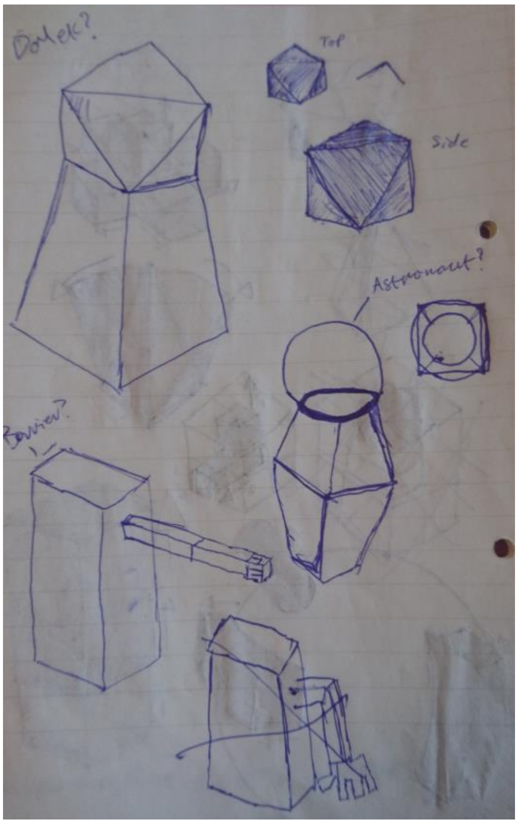

Figure 2

Above is a selection of the first drawings made on this project. They show forms and the motion that could come from them. The meaning of each is wildly different, with each form using only a single movement to express itself. This process taught me about the importance of a thoughtful movement that would communicate all that was necessary to an audience.

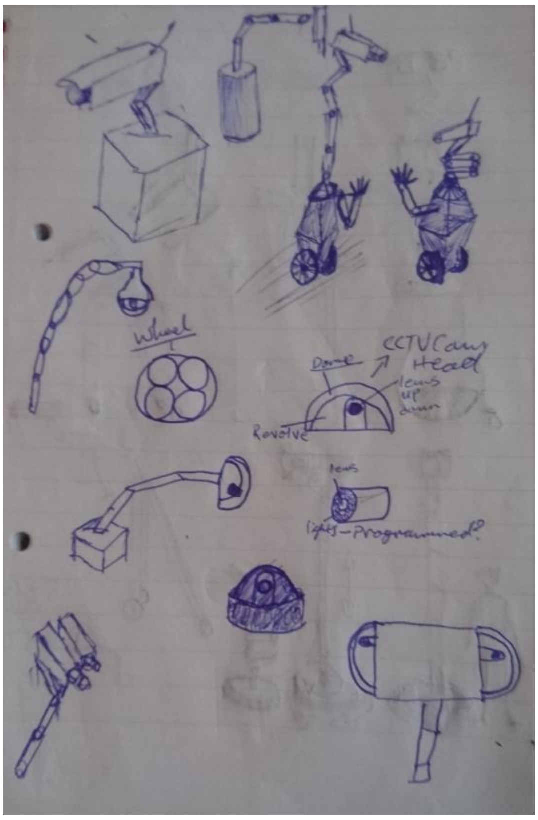

Figure 3

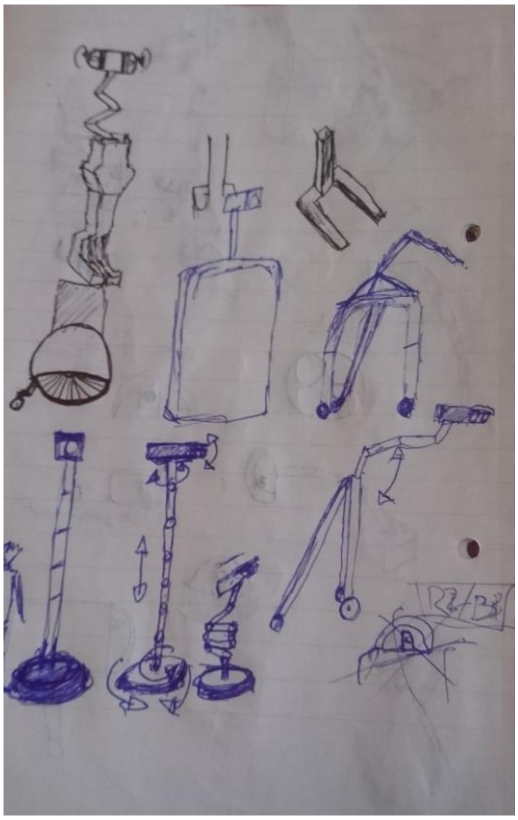

Figure 4

Above are examples of the definite features being sketched out and played with. The character of the Conductor was originally built as a surveillance robot, an intelligent, mobile and fully aware CCTV camera that could interface with humans and also pose as an unobtrusive character. To achieve the right look, I began by referencing real-world CCTV cameras for my sketches and making modifications. I also toyed with the idea of using the same essential form, in which can be seen in Fig.3. Fig.4 shows the start of the base form and the mobility system. Knowing this was a machine built for city use, I took the liberty of not making it all-terrain, and focused on a futuristic mobility system. This system could not be a simple set of wheels, but audience more complex system that would surprise and subvert the audience's expectations.

During this stage of my conceptualization process, I found the concept of omni-directional and mecanum wheels, which is what I ultimately stayed with for my final design. I also established that the Conductor would be a part programmed, part puppeteered character. This was a decision based on my

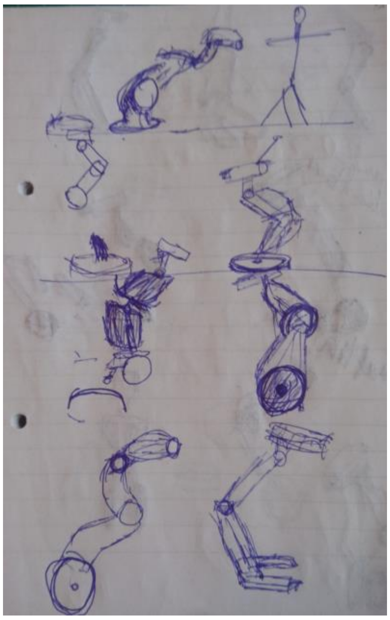

Figure 5

Figure 6

time constraint. As I had only a few months to create the animatronic, with even less time to rehearse in our performance space, I knew it would be too difficult to orchestrate an entirely preprogrammed performance. The choreography alone would take weeks to prepare, so instead I decided that the Conductor would be puppeteered, although it would still appear autonomous onstage.

Figure 7

Figure 8

As I refined my design, I gravitated toward a human form that was not unlike a person waiting patiently, as though they were waiting in line or contemplating their day with a happy heart. This embodied the spirit of the Conductor so well that I began to illustrate technical drawings with this form in mind. Above is a small selection of the numerous sketches made in order to find a suitable silhouette. In Fig.7, you can see the human form that I am attempting to emulate. Once I had decided on this design and was happy with the outer shape, I began to develop an inner mechanical skeleton to be the main controlling force, shown in Fig.9.

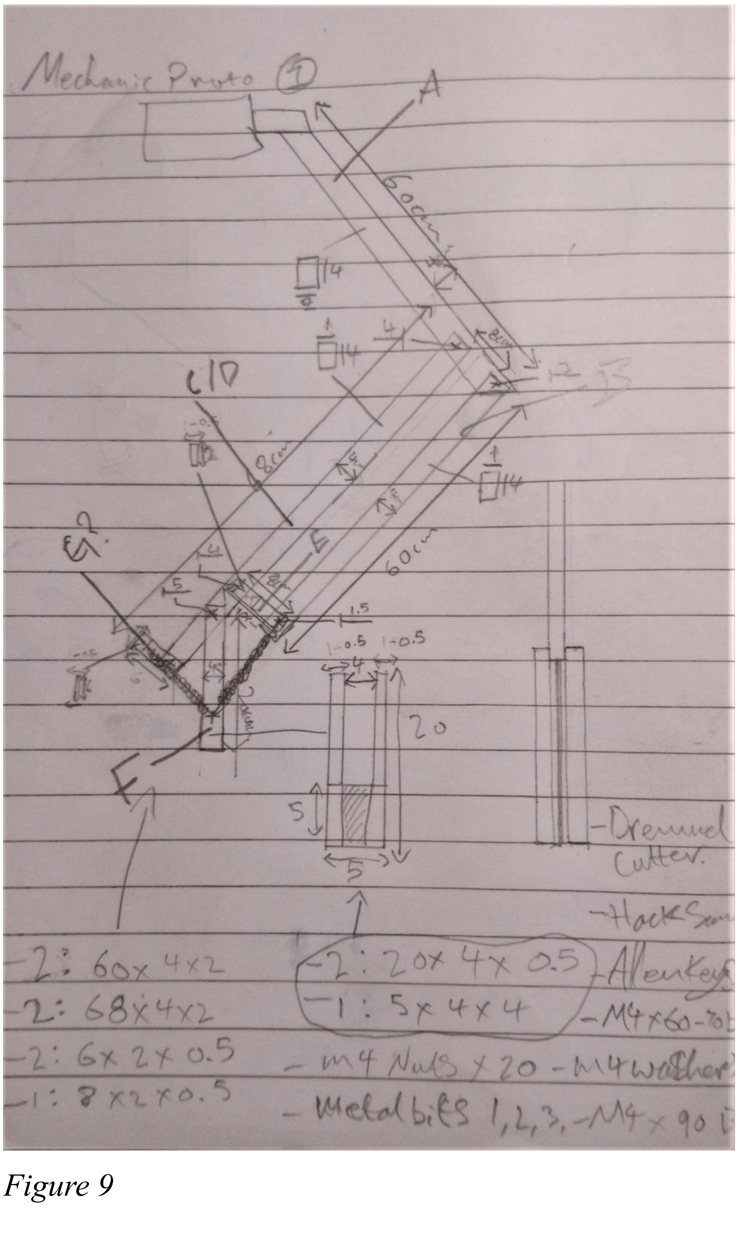

Figure 9

The drawing above illustrates a “lamp-like” armature. I took inspiration from lamp designs to keep the body upright and facing forward.

Wood

During the LET Award preparation, I took the opportunity to construct a hand operated version of the above design. I would be able to not only get a true sense of scale and iron out some of the mechanics, but also be able to test out the articulation of the puppet in front of an audience.

Figure 10

The puppet was furnished with eyes, paint and a suitable base fitted with caster wheels. Fig.10 shows a puppeteer manipulating the hand operated puppet. This design was indeed oversized, but allowed me to experiment with the articulation and scale down the measurements for the next iteration of the prototype.

Foam Core

Once the award performance was completed, I set my sights on the construction of a working prototype. Before creating a full-scale prototype, I began by constructing a scaled-down foam core version. This allowed me to work from a rough three-dimensional reference that could be tested in a

Figure 11

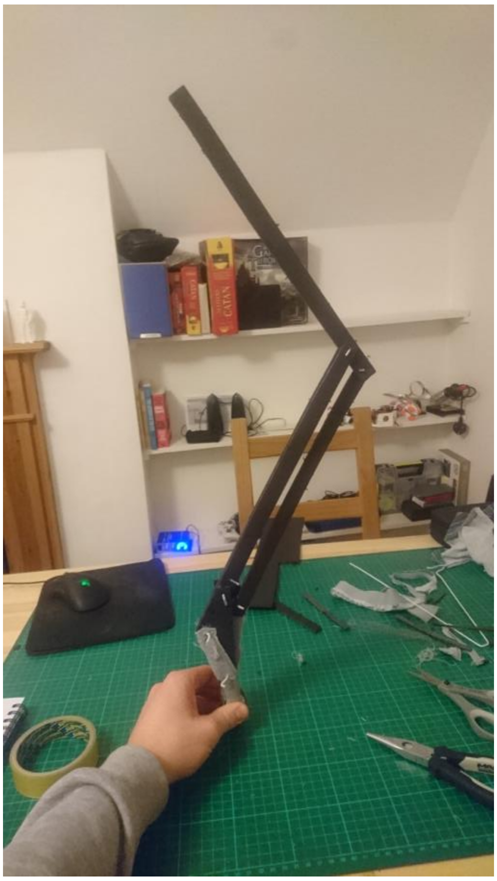

Figure 12

limited fashion. The foam core figure shown in Fig.11 and Fig.12 was built to test the basic articulation using spring supports. The grey elastic, which would be replaced by springs, pulled the upper sections of the body into an upright position. This design would, in theory, assist the motors in raising the upper body.

Metal

After the foam core model, I built the animatronics' skeleton out of aluminium. I cut pieces of 15x15mm and 20x20mm aluminium tubing and fit the pieces together with sets of Nyloc nuts and bolts.

The build only took a few days to complete, with the measuring, cutting and drilling all performed in the university's workshop. Before long the body assembly was constructed, and I employed the use of tension

Figure 13

springs to hold the body in an upright position, as shown in Fig 13.

Figure 14

Circuitry

The circuitry involved using a combination of an Arduino Uno, a set of L293D motor drivers and an Xbee module for wireless control; Fig.15 illustrates the full system. The three motor controllers connect to three stepper motors for a total of three points of articulation. The left, right, up and down of the head, and the

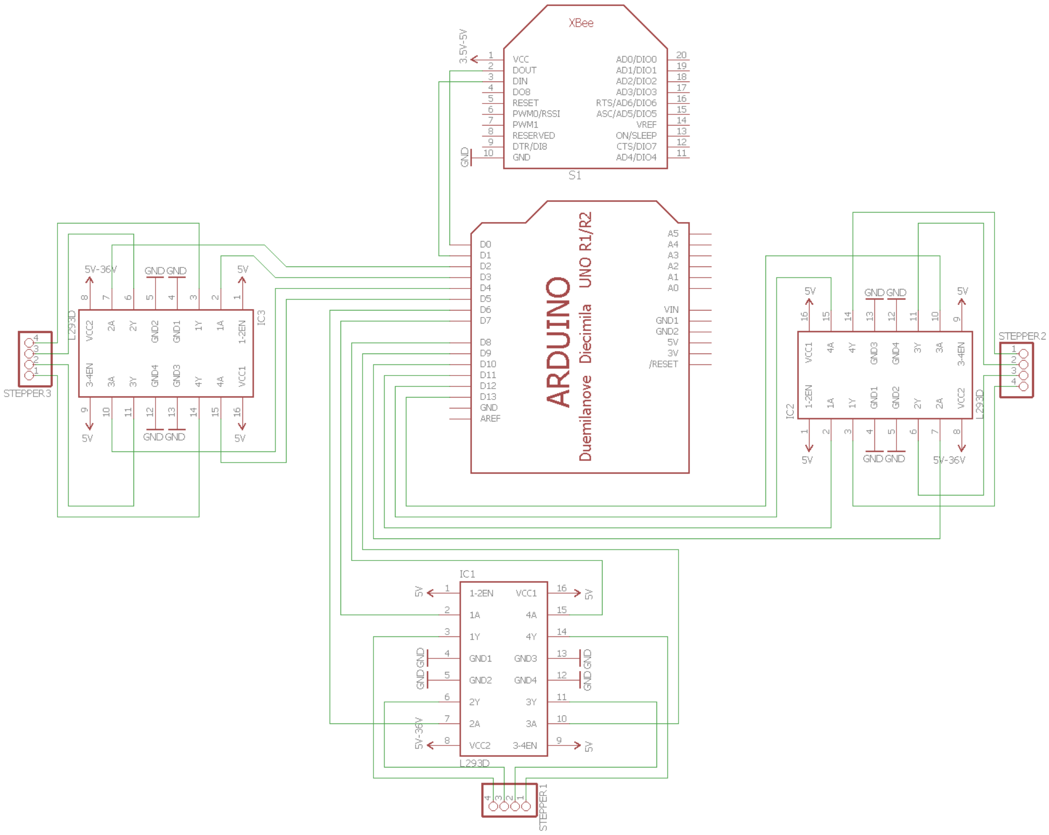

Figure 15

bend in the middle of the body. The Xbee module connects to the same network as another Xbee, which during my tests was connected to a computer running a small Processing app that recognizes keystrokes and sends them over serial to the Xbee on the animatronic.

I tested the system with multiple types of stepper motor. I started with a relatively small Kysan 1124101, which had a Nema 17 chassis and a holding torque of 2.4kgf.cm at 0.33A[14]. I quickly found this motor to be highly underpowered and moved to a larger Nema 23. This motor came with a much larger 1.26Nm of holding torque, but at the cost of 2.8A per phase, making the motors almost impossible to run

[14] Link to my video of actuator tests https://youtu.be/NVlyRGxffkA

off a smaller battery. Though they were not used in the final design, I was able to determine that a smaller motor that was geared down could have the ability to lift the animatronics' mechanical elements. Next, I tried using a 5:1 geared Nema 17 stepper motor. This particular model had a holding torque of 2Nm at 1.68A per phase. Even at this ample strength and low current draw, the motor was unable to lift any part of this first prototype.

At this point I found that the actuator design did not work for any point of articulation due to the weight of each section, and the power would not be capable of performing with the load of current needed while remaining wireless. The body was too large and far too heavy, resulting in the stepper motors not being able to even hold themselves still. The body would collapse on itself regularly. I made very little progress at this stage, and after many days of testing I realised that my designs were inherently flawed. The L293D could handle a range of 4.5V – 36V, but only output 600 mA and 1.2 A at peak. This was far too little, as the motors would be reaching the peak on their normal operation. After some contemplation and research, I found no practical solution to the problem at hand. I made the executive decision to redesign the prototype's upper body.

The final design

Sketches

The redesign gave me a chance to consider the project again from another angle. I knew which parts of the character where essential for the communication of its emotions. The eye was both a symbol of its past purpose as a security drone, as well as also its most expressive feature. The second essential feature were the wheels for the base platform movement. These wheels would not only need to give the character freedom to move, but also a modern dimensionality. What I needed to remove from the previous prototype was the "waist", as this was the main culprit of the top-heavy construction. The overall construction needed to be shorter and have a lower center of gravity to maximize stability. Taking all of this into consideration, I decided to design the "body's" movement around a central axis. The body would rotate entirely like a spinning top, and the head would be able to rotate via an axle assembly, similar to a

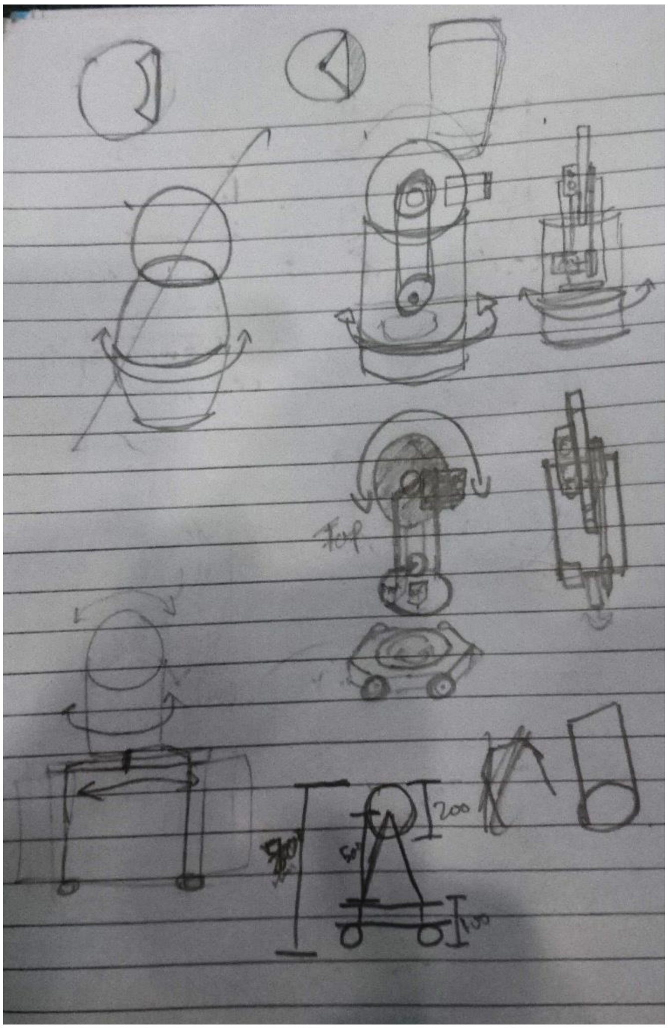

Figure 16

bicycle wheel. The articulations on the body would be separate from the platform and from each other, allowing them to spin with a full 360-degree range of motion independently. With the combination of the two independent halves, the platform and body and their respective range of movement, this design allowed for a great deal of animation at the hands of a puppeteer, while remaining practical in terms of weight distribution and mobility.

Mecanum Platform

In a previous assignment, I attempted to produce a 3D printed version of an omnidirectional robotic platform (Fig. 17). This system used stepper motors, 9V batteries, L293D motor driver, an Arduino Uno

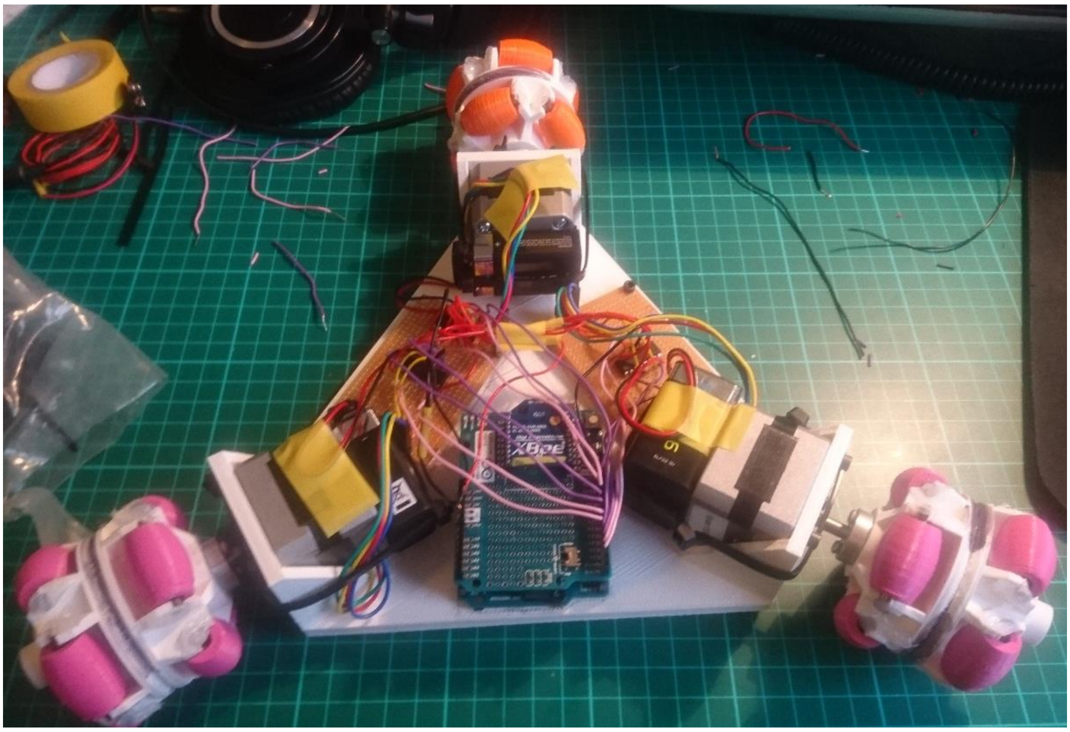

Figure 17

and an Xbee module for control. This project was a success in terms of what I learned through its failures. Firstly, the stepper motors were far too underpowered for the necessary holding torque and RPM; if there was any undue friction or stress, the wheels would simply stop rotating. Secondly, the 9V batteries were a poor choice, as they would run out after a short twenty-minute use and are very expensive. Thirdly and finally, the wheels themselves had no grip and unless the platform was operating on a smooth, flat surface it would only spin on the spot.

After my experience with the 3D printed platform, I opted to purchase manufactured wheels to ensure stability and grip. During my research, I found that the omniwheels on the market were by and large out of my budget. Instead, I turned to mecanum wheels as a suitable alternative. Due to their construction, the mecanum wheel can be the same size as its omniwheel counterparts, but have a higher weight capacity.

Figure 18 60mm mecanum wheel

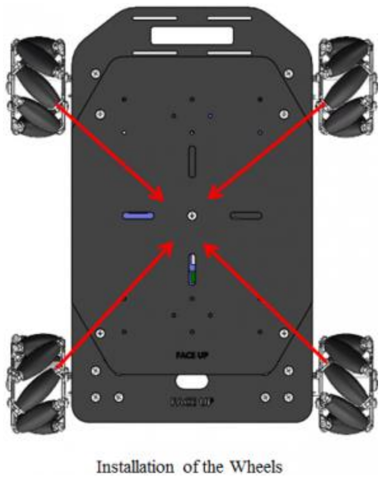

Figure 19

Fig. 19 demonstrates the orientation of the wheels to the centre of the robotic platform. The rollers are positioned at a 45-degree angle to the plane of the wheel and at a 45 degree angle line through the centre of the wheel. The result is a traction system that, when force is applied to the wheels, force is equally applied in right angles to the opposite wheels. This allows for the platform to move in practically any direction on a two-dimensional plane. For example, when both the left-hand wheels are spun towards each other inversely and the righthand wheels are spun away from each other, the platform will strafe to the right and vice versa (see Fig.20). Not only does this design provide the support needed, but the unexpected and subversive verity of movement that can be used for character expression.

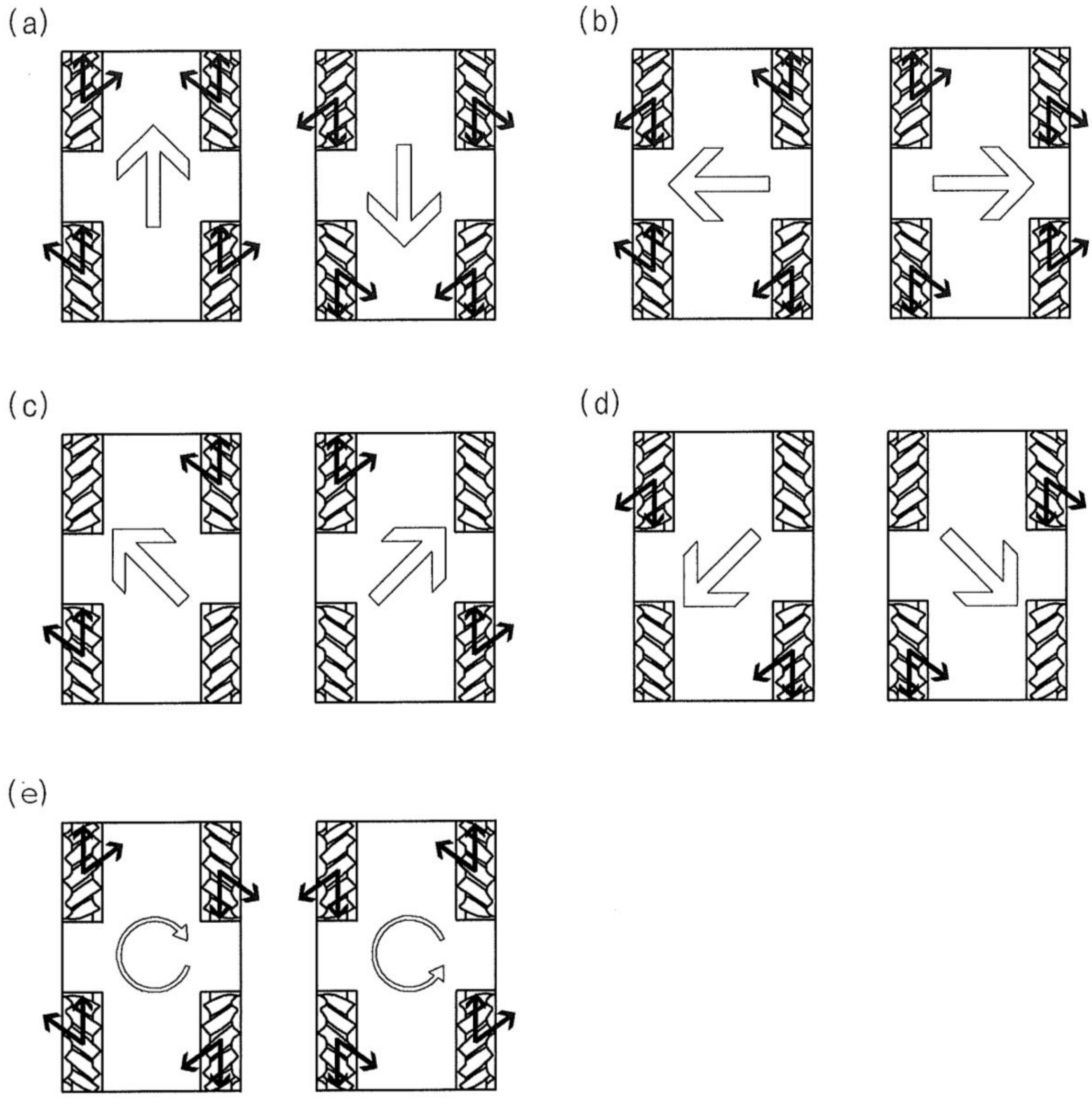

Figure 20

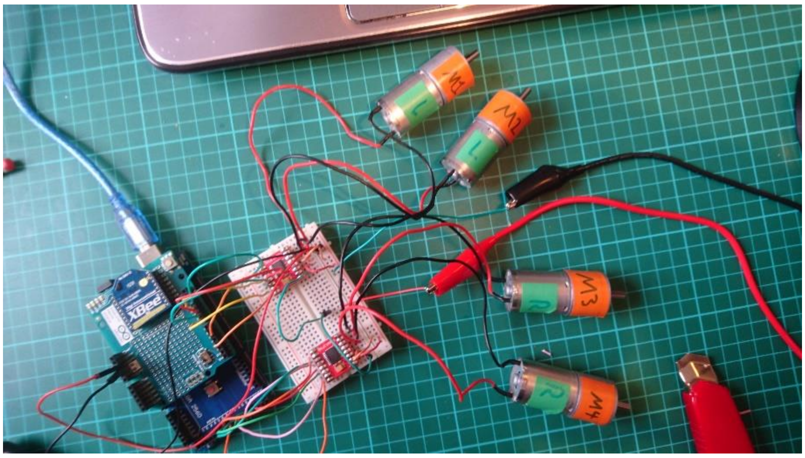

Figure 21: 25GA-370 DC motors in breadboard test with TB6612FNG motor drivers.

I purchased 25GA-370 DC motors that are geared up with a load bearing speed of approximately 260rpm. They run on 6V with a no-load current of 600mA and a peak load current of 1600mA, far lower than any of the stepper motors I had previously tested. These wheels and motor attach to an acrylic platform to which the circuitry can be mounted. The initial tests were highly successful[15]. I was able to test the platform with a bench power supply and the Xbee communication from my previous omniwheel prototype. The platform proved to be fast and responsive, even when weighted.

15 Link to my video of mecanum platform test https://youtu.be/1LyABGPvbic

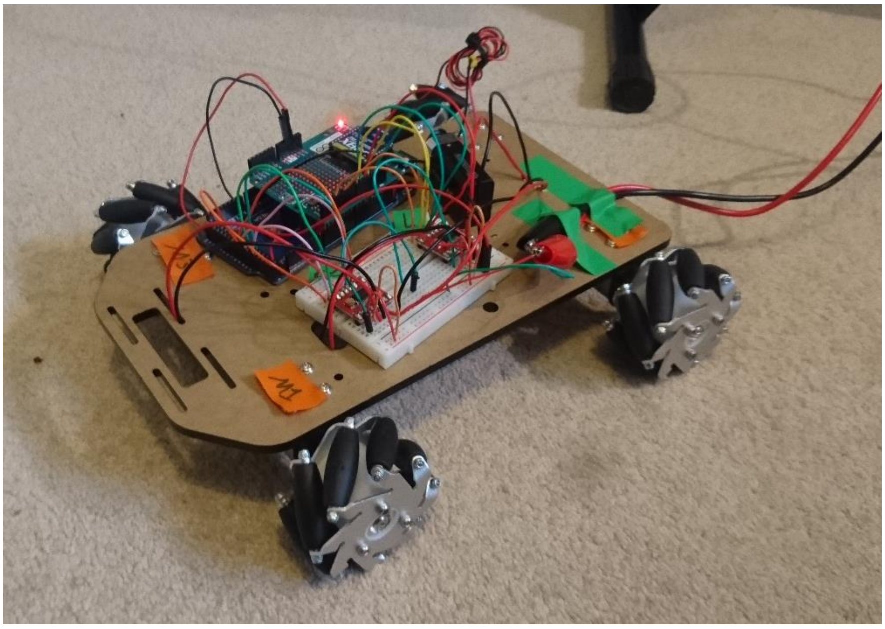

Figure 22 Testing setup with breadboard.

In need of new motor drivers, I opted for the Sparkfun TB6612FNG breakout boards. These small profile drivers are only rated up to 15V, but they can provide 1.2A on average and 3.2A at peak consumption and are fitted with a thermal shutdown circuit to prevent overheating. These drivers were perfect, as they could easily provide the load current for the DC motors at a peak of 1.6A current draw. The other benefit is their modularity, which I factored into my circuit design for easy testing and repair. The TB6612FNG needs at least seven digital pins to run two motors; because of this I used an Arduino Mega 2560 for the platform with a Xbee shield to account for all the pins necessary.

Platform battery mounting

The batteries for the mecanum wheels, two 6V 5000 mAh packs, were fixed to the bottom of the platform in many ways over the period of construction and testing. Firstly, I simply taped them to the underside of the platform. After a short period of testing, I opted to attempt securing them with Velcro. The Velcro held both batteries in place, although they were prone to wiggling from side to side due to the placement of the Velcro. After some weeks of testing and wear and tear, the Velcro would not hold the batteries closely to the underside of the platform anymore, I decided to build something more permanent.

My solution was to fabricate a clear acrylic cover that would be held in place by bolts and Nyloc nuts. The cover was drawn in Inkscape and cutout with the Fusion M2 40 Laser cutter. The clear acrylic allowed me to mark out the mounting holes on the mecanum platform. After drilling the mounting holes, I used a heat gun and a vice to heat up, bend and cool down the tabs on all sides of the cover.

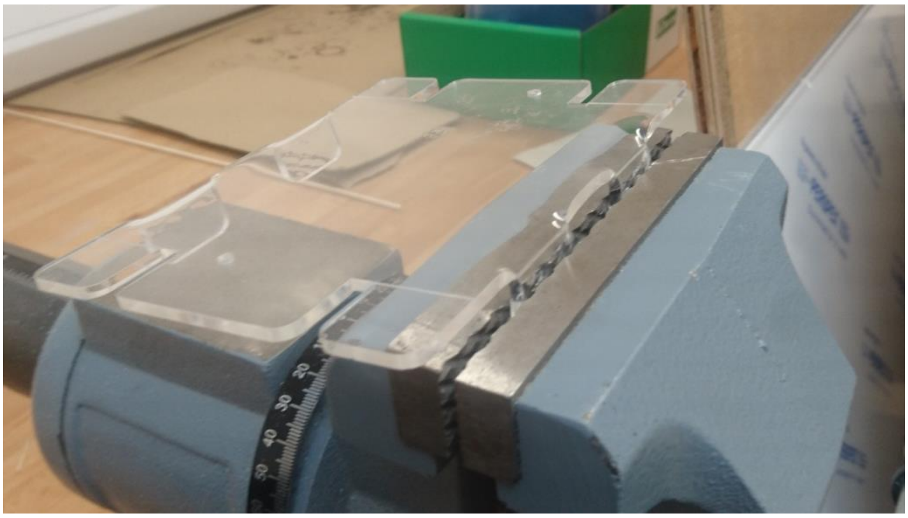

Figure 23

As the tabs were hand bent, they were fitted snugly around the batteries. The set of mounting holes were connected with a 40mm bolts, wide washers and Nyloc nuts for a secure, safe fit.

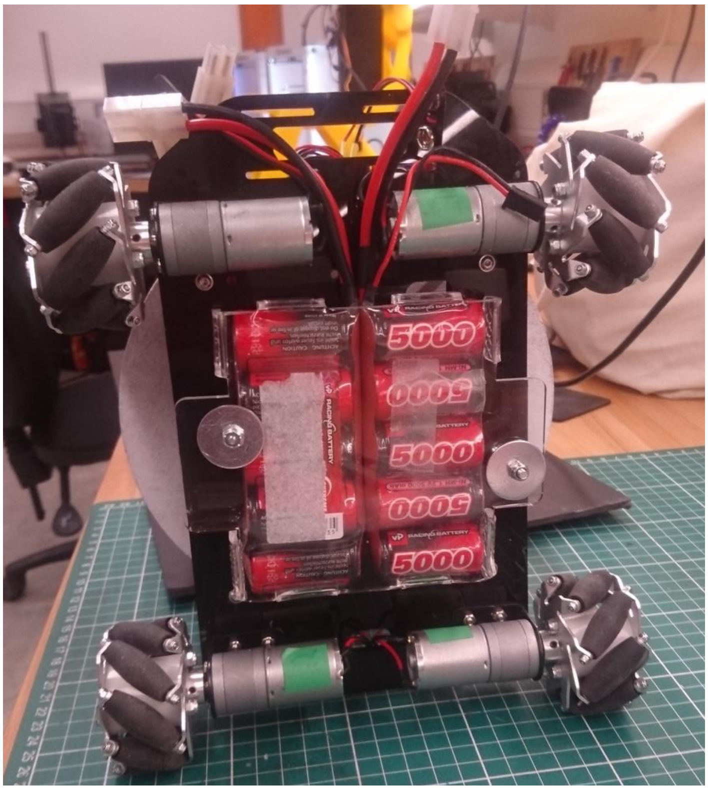

Figure 24 The battery cover bolted in place

Design of the New Body

I began by modeling the components of the new design in Fusion 360, so that I would be able to scale and transform the design as needed during the build process. The new design's body was comprised of five structural components, the lower plate, two axle mounts, the axle and the head. The body would rest on a separate platform connected to the lower mecanum platform. The two sections would have a large bearing sandwiched in-between to improve stability and reduce stress on the motors.

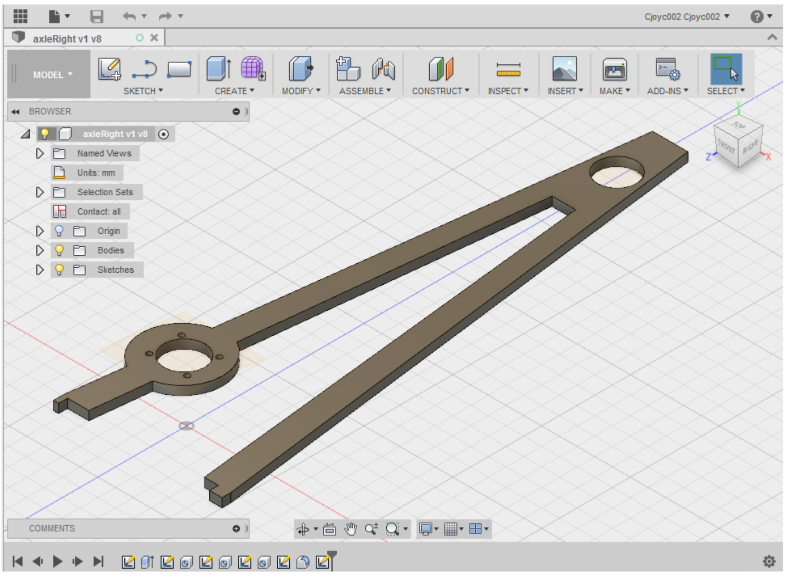

Figure 25 The axle mount

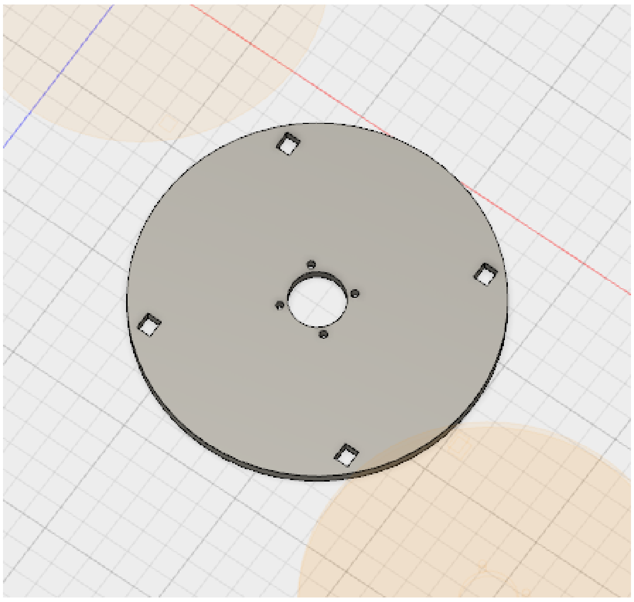

Figure 26 The base plate

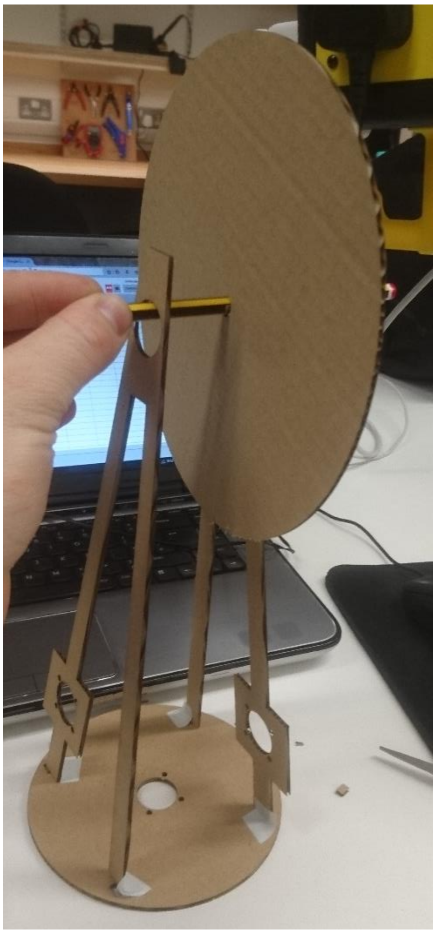

Figure 27

Fig. 27 demonstrates a small scale model of the assembly of the body section. This initial cardboard construction was made with a Fusion M2 40 laser cutter. Since it is a cheap, flexible material that can be easily cut, the cardboard allowed me toto make sure that the construstion made sense in a 3D space.

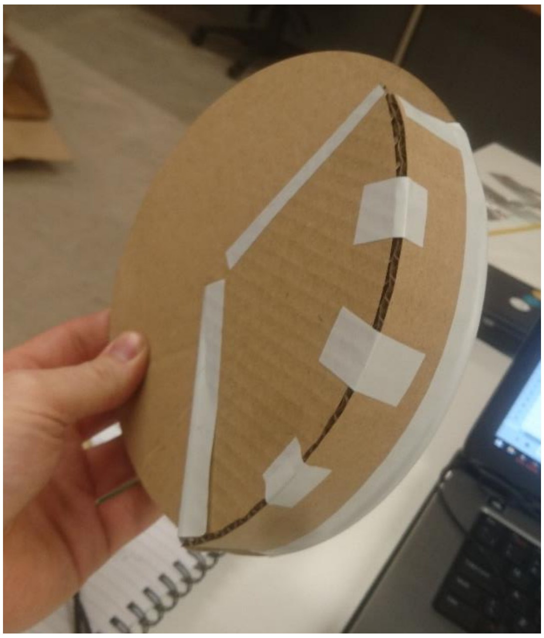

Figure 28

Fig. 28 shows the first prototype of the eye. A module assembly was going to be mounted like a window on the front to emulate a cross section of an eyeball.

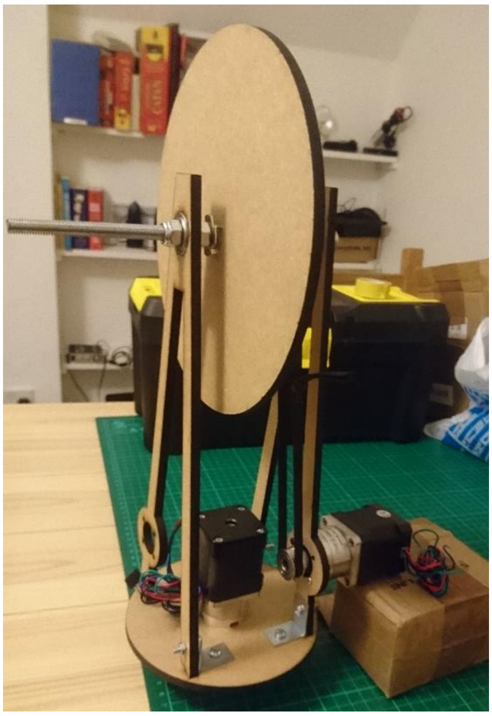

Figure 29

Fig. 29 is the first “hard” assembly of the body. Laser cut MDF was used for the main components bar the axle. The axle is an 8mm threaded rod so that the head can be positioned using T-Nuts, which are bolted into place by Nyloc nuts. T-Nuts have four spikes that are driven into the soft wood and a short-threaded tube extruding from the centre. Both axle mounts have a 22mm skateboard bearing pressure-fit into their top mounting hole. The centre bore of the bearing is 8mm, which allows the threading rod to sit snugly in either side of the axle mounts which are then bolted from either side by Nyloc nuts. A timing belt runs from a timing pulley on the 8mm rod down to another timing pulley attached to the Nema 17 stepper motor. This assembly allows the rod to spin freely with the head attached.

Now that the basic construction was finished, I could attach the upper body to the mecanum platform. Fig. 30 illustrates the first construction of the Conductor. In this first attempt, the Nema 17 stepper motors were used for testing in tandem with a 3A bench power supply.

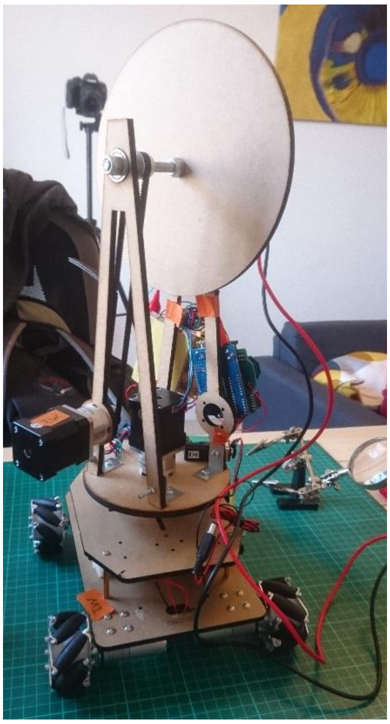

Figure 30

After several tests, I found that the scale to be sturdy but too small, and the stepper motors proved to be inadequate. The stepper motors in question were still the 5:1 Nema 17 from the previous prototype. The motor drivers could not provide enough current over long periods of time and would shut off after overheating. I returned to my original design and updated it to reflect the outcome of my tests. The timing belt needed to be shorter and the pulleys closer, and the motors needed to be changed. I decided that geared down DC motors would achieve the speed and torque I required compared to stepper motors, due to their power consumption. I decided against Servos due to their high cost. I understood that DC motors would not be programable or as accurate, but these factors were less important than their strength and cost, as without adequate torque the body would not move.

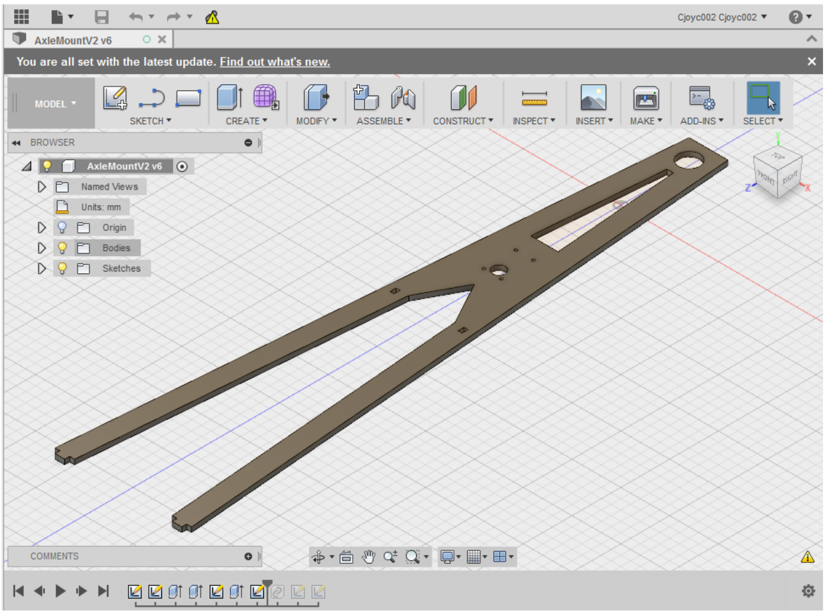

Figure 31: The new axle mount with the new motor mounting holes.

Figure 32: The new DC motors attached to the axle mount and the base plate.

The DC motors I chose are the Zheng ZWL-FP100 at 12V and 100rpm with a worm screw gearing for maximum holding torque. To prevent instability in the body I used aluminum struts to hold the upper half of the axle mounts as still as possible.

Figure 33: Assembly with angled struts

Design of the New Head

I performed weight tests with the motors and found that they were capable of bearing 500g on the outside of a 200mm disc for its head. However, I needed to change the head, as the excess weight was making the body top heavy, which caused it to sway violently when driven. To combat this, I devised a new design for the head. In keeping with the surveillance and eye aesthetic, I opted to create a camera-like assembly, with a lens at the front that would act as the eye.

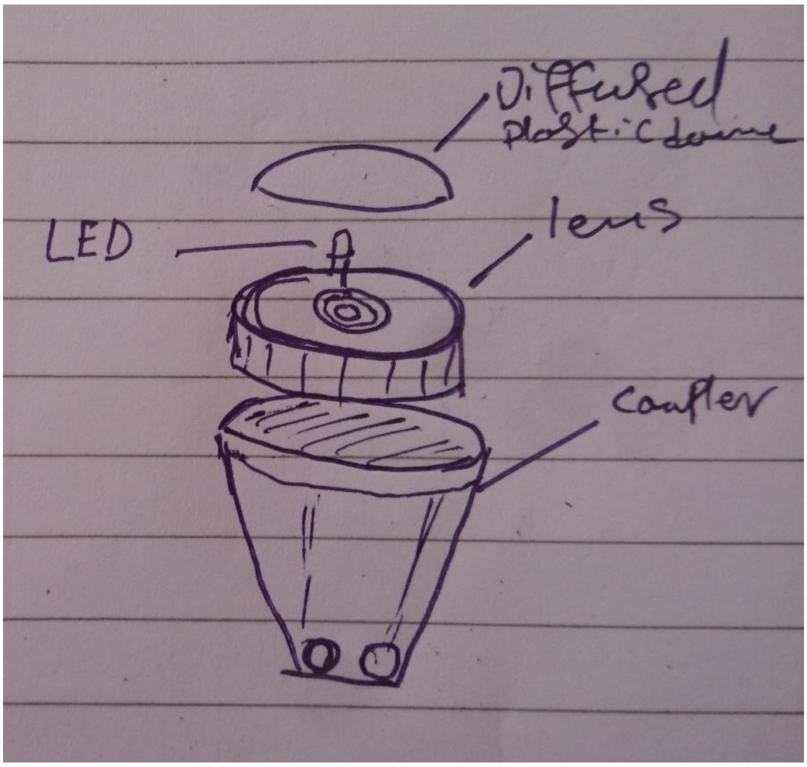

Figure 34

The holes in the bottom of the coupler in Fig. 34 were used to bolt the camera assembly to the "neck" of the robot. The inside of the coupler is hollow to allow an Arduino Mini Pro and Xbee module to be inserted, and the forward lens has a hole for an RGB LED to poke through. The dome on the front would be 3D printed, and lens assembly would screw onto the coupler with 3D printed threading.

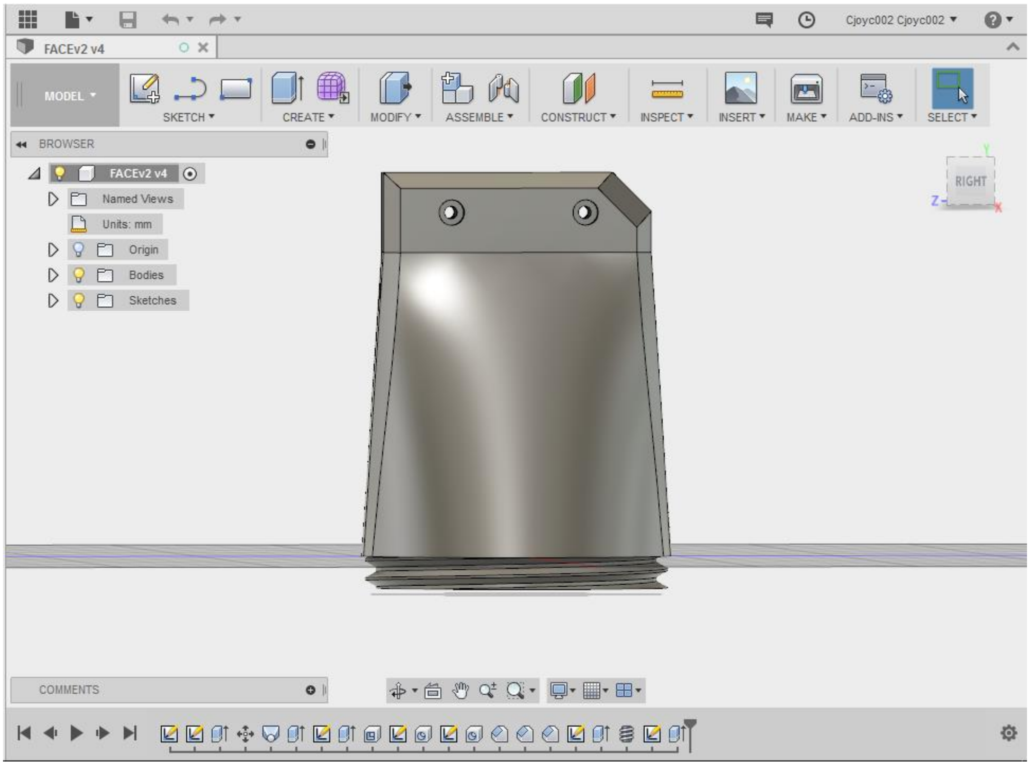

Figure 35: The coupler in Fusion 360.

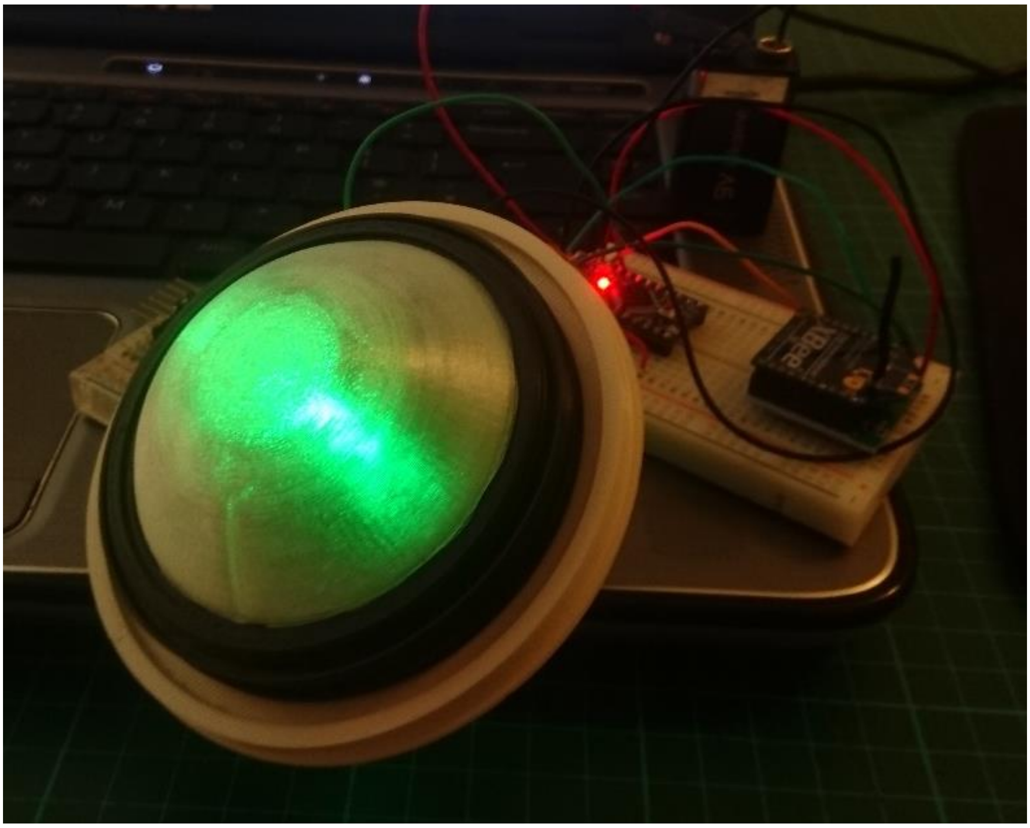

Figure 36: The lens illuminated.

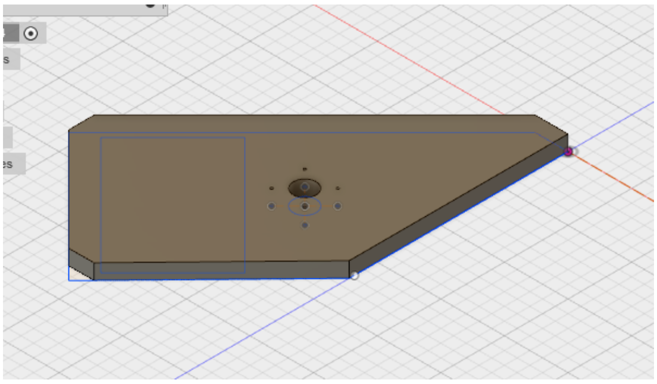

Figure 37: The neck

The neck was designed to counter balance the camera assembly and the 4 x AA battery pack that powers the Arduino Mini Pro, Xbee and RGB LED. The battery pack is attached with a zip tie to the rectangular space on the left side of the axle hole in Fig. 37, and the camera assembly attaches to the angled edge on the right.

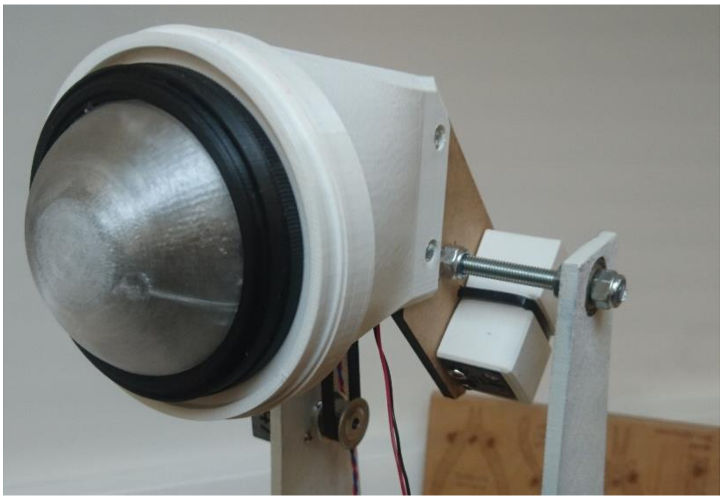

Figure 38

The battery pack in Fig. 38 is shrouded with a 3D printed part to give it the same look as the rest of the character. The black lens ring was not modeled by myself, but taken from Thingiverse. It is a section of HAL 9000's faceplate as modeled by CONCENTRIX[16] . Thingiverse is a great resource for 3D printable models, though to use them you must first make sure they are under the right copyright license. As my

[16] Link to CONCENTRIX's model www.*thingiverse.com/thing:1805762*

production and robot are not being built for monetary purposes and simply for education, I was free to use the model from CONCENTRIX.

Connecting the Body and Platform

The body and platform are connected with a large bearing and a mounting hub. Fig. 39 shows the bearing attached to the body section with the motor shaft through and the four corners ready to accept the upper disc of the platform.

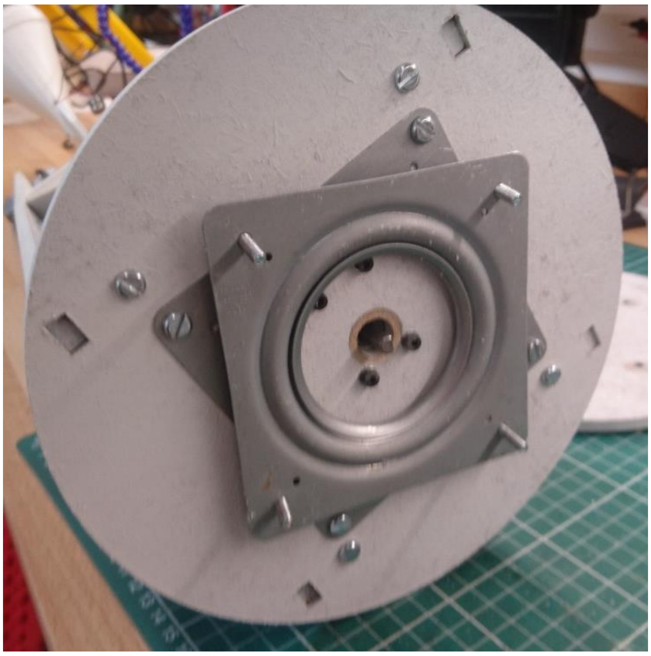

Figure 39

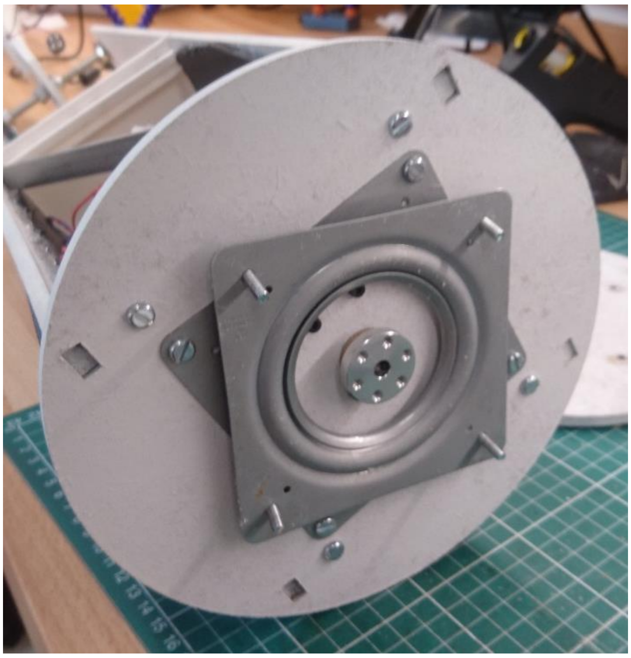

Figure 40

Fig. 40 shows the assembly now with the mounting hub attached to the motor shaft. This hub is also ready for the upper disc.

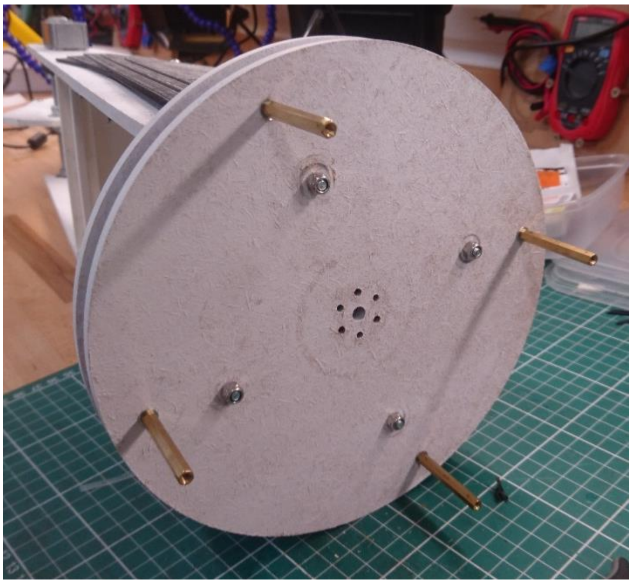

Figure 41

In Fig. 41, we see the upper disc is now secured, with the four corners of the bearing and the mounting hub in the centre. While this assembly is practical, the weak spot is in the mounting hub. Two grub screws hold it is place, and even with Loctite Threadlock, they become loose after approximately two hours of use. This aspect of the build would have been addressed further if more time was available. A way I could improve the stability is by either implementing a bearing the same diameter as the upper disc, or by using a hard nylon ring as a bushing around the edge of the upper disc.

Power

Now that my design and components have been finalized, I could begin finalizing how to power the system. From the start, I wanted the Conductor to be wireless, so I decided to use rechargeable NiMH batteries. I chose these for multiple reasons: firstly, I needed a battery that could match my motor systems at their respective voltage of 6V and l2V as NiMH batteries can be multiplied to those voltages as a standard. Secondly, the alternative of a Lithium Polymer battery not only does not come in 6V and 12V as standard, but is far more expensive in terms of mAh per battery. My batteries came to 5000mAh, which fulfills my need, plus extra for safety; the LiPo alternative would have cost double for anything close to that capacity. And thirdly, the heavy weight of the batteries played in my favor by keeping the platform held to the floor without the motion of the body upsetting the balance. These attributes made for an effective power source. On later testing I even found that I could run my system for four hours before the batteries started coming close to running out of charge[17] (see footnote for video).

To power the multiple Arduinos onboard, I opted to use AA batteries. I used a housing for six batteries equaling 9V for both the body and platform Arduinos, and a housing of four batteries for the eye. The power for the eye only needed to power the Arduino Mini pro (approx 30mA), RGB LED (max approx. 60mA) and the Xbee (50mA), which totals 1.4A of current. The power for the other two max out at a very similar 1.2A, somewhat less as the TB6612FNG current draw is negligible. AA batteries provide enough voltage, and if rechargeable, they can be anywhere from 600-2000 mAh in capacity, more than enough time for my use; each full run-through of the play was only forty minutes.

Circuitry

The circuitry was designed for simplicity and modularity. Only the most important connections are

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17 Link to my video of full function battery test https://youtu.be/aHEChD8rodQ

soldered in place, the rest have pins and designated female pin headers. To protect sensitive circuitry, I made sure that the system could be easily replicable in case of a fault. I began my preliminary circuitry tests with breadboards.

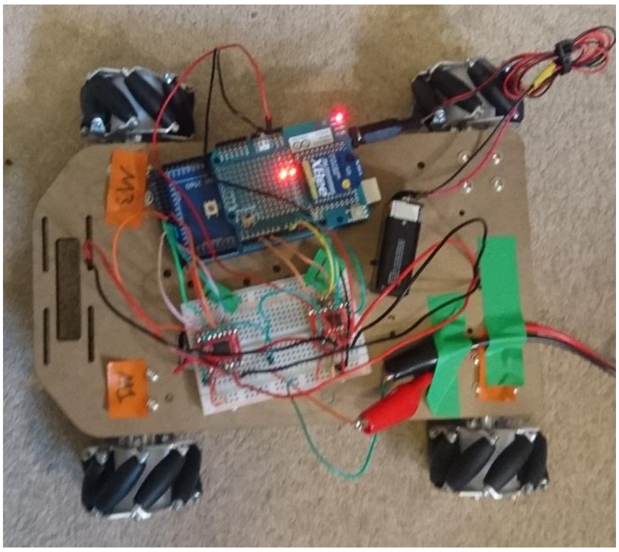

Figure 42: Platform with breadboard circuitry

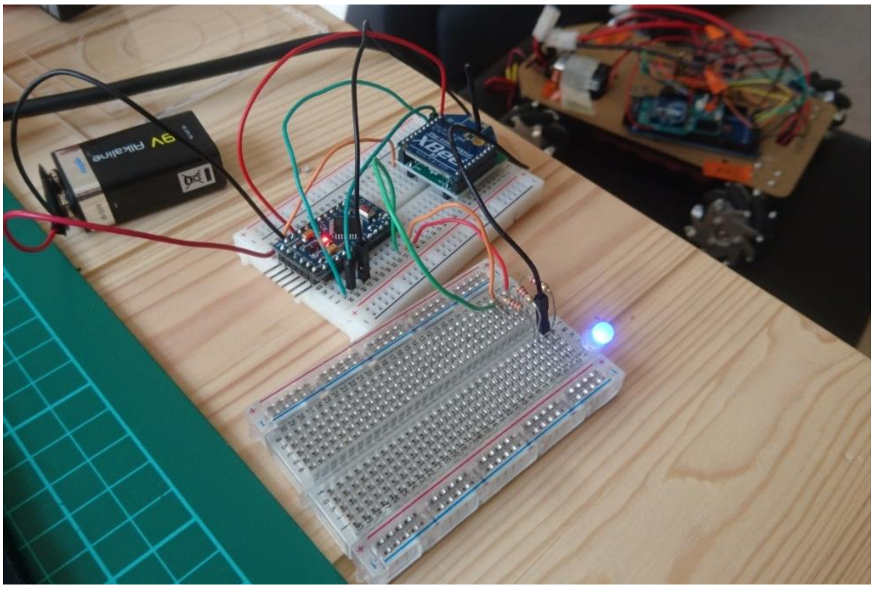

Figure 43: Eye circuit

Once the breadboard versions of the circuits were tested, I moved on to soldering the wires to a matrix board, covering the ends in heat shrink tubing and hot gluing any open connections on the surface of the matrix board. Although it did not look pretty, this served as a robust method for the rest of the production.

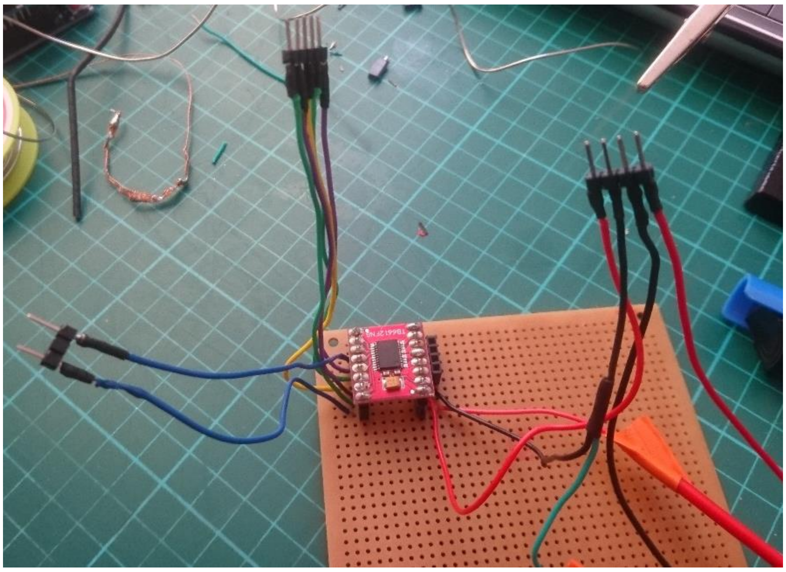

Figure 44: Motor driver for body with heat shrink protected header pins

As seen in Fig.44, the wires from the motor drivers were soldered into the matrix board and connected to the male header pins in order to be inserted into the Arduino. I designated two rows of female pin headers for the motor driver's breakout board pins for easy replacement. A row of four female pin headers were placed next to the driver to allow the motor wires be plugged in. I repeated the same design on the other two custom circuit boards.

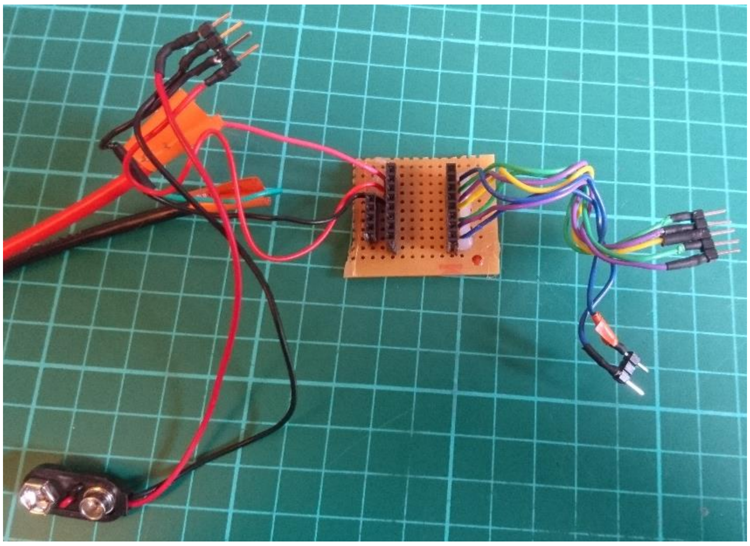

Figure 45: Body circuit board

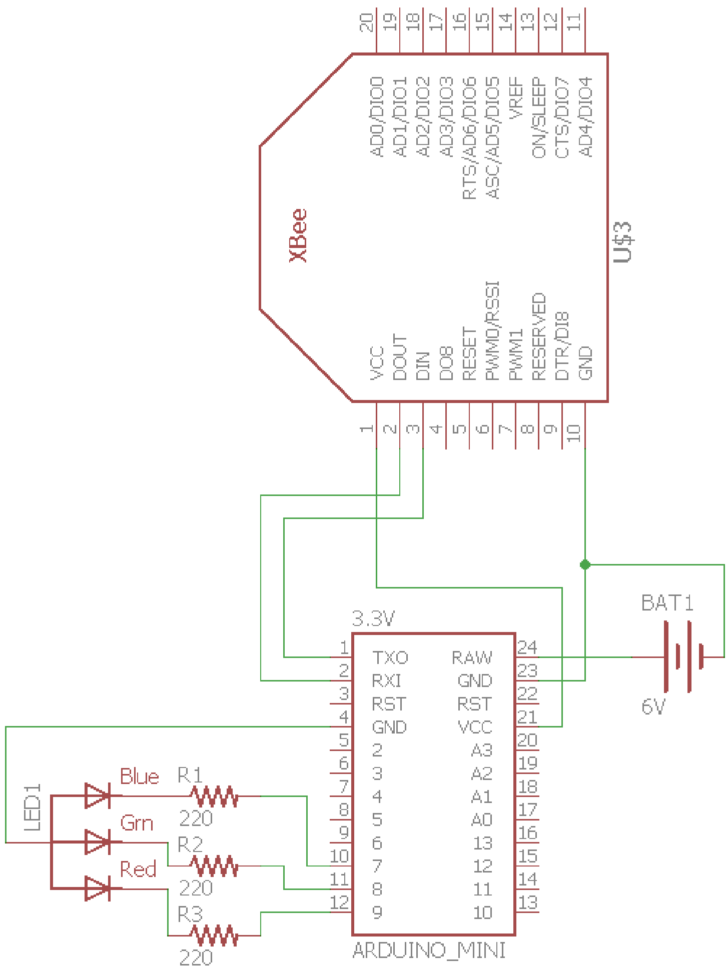

Figure 46: Eye circuit schematic

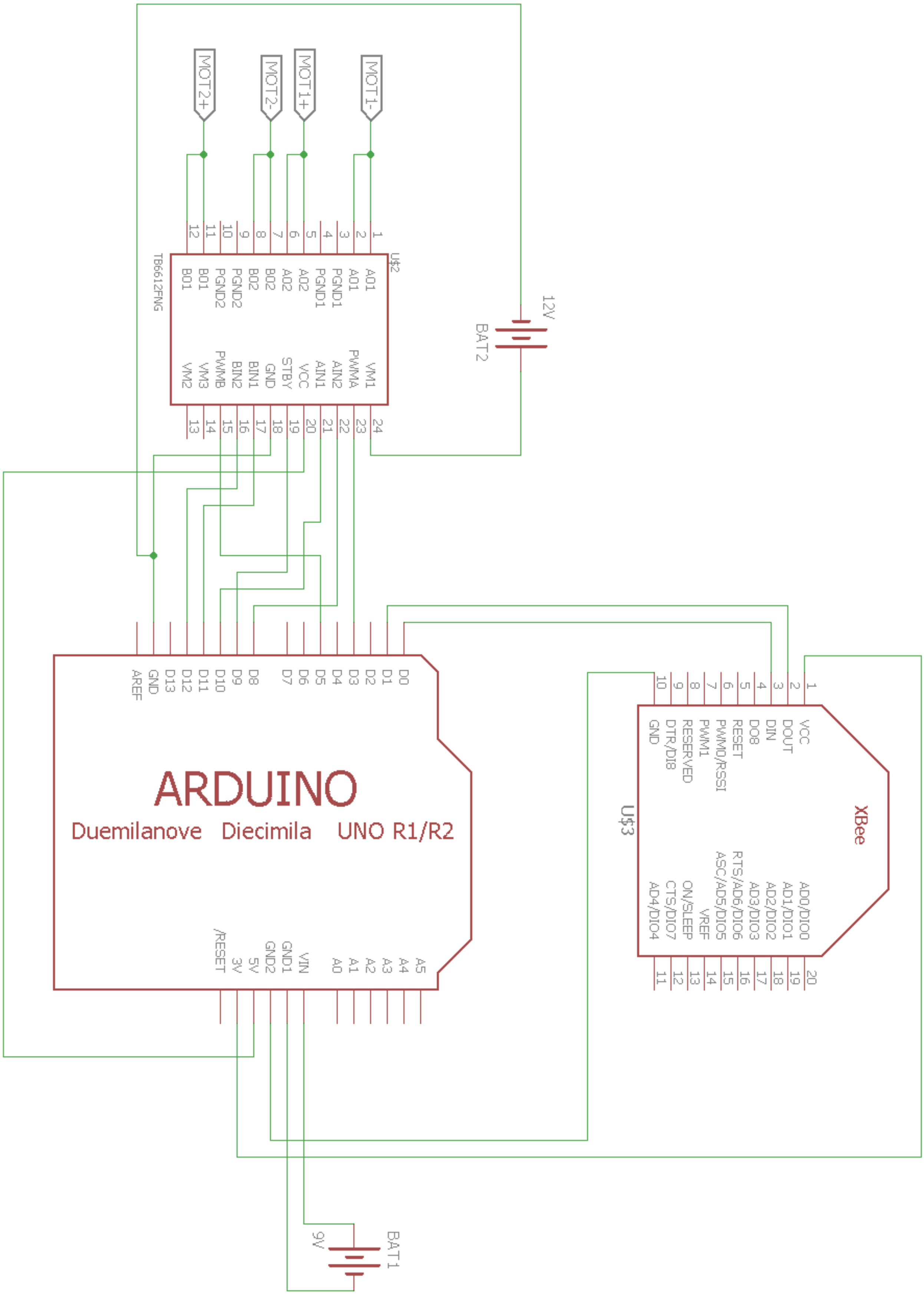

Figure 47: Body circuit schematic

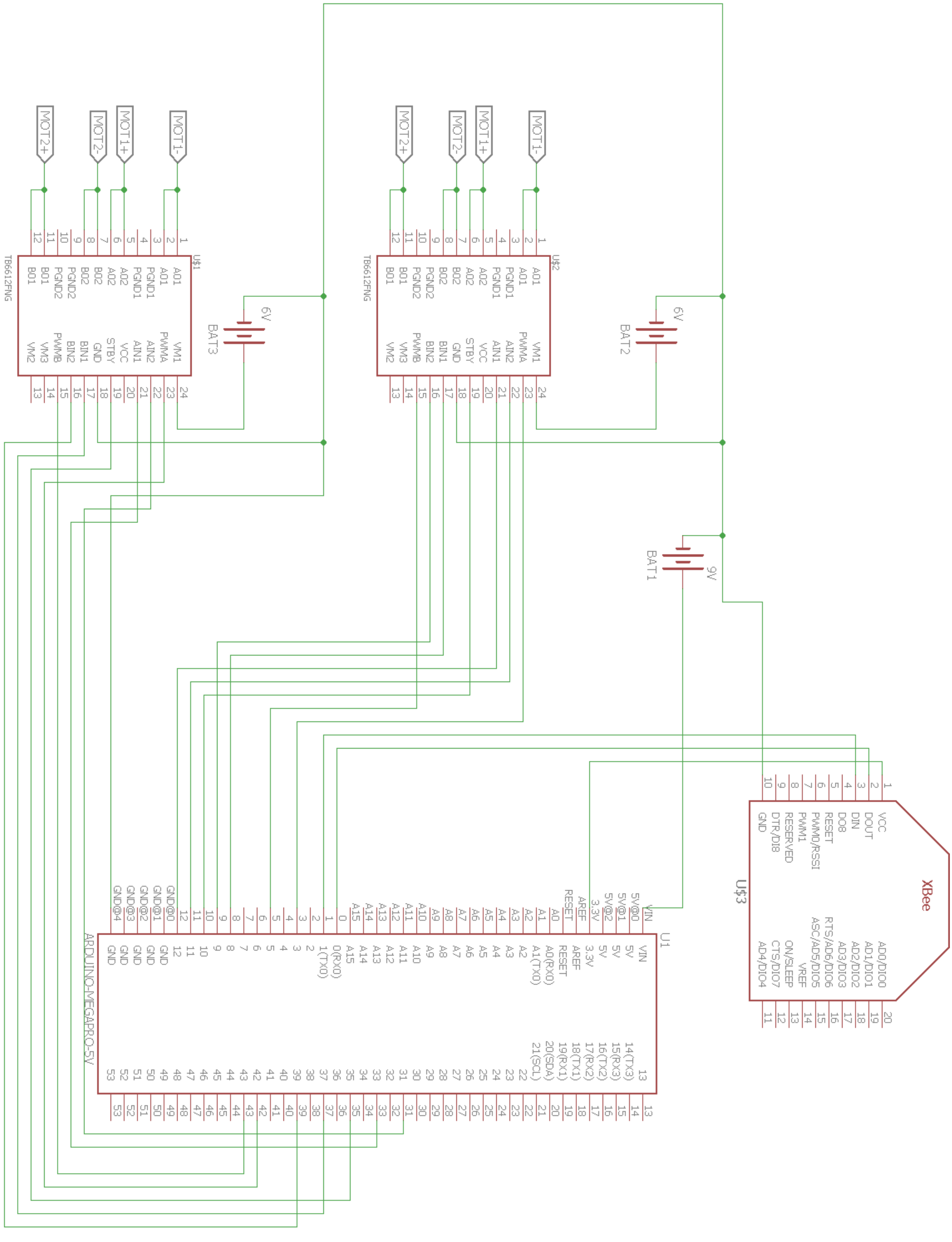

Figure 48: Platform circuit schematic

Final assembly

Now that the structural and electrical construction was complete, it was time to decorate and finish the aesthetic elements of the character. I began by disassembling everything and sealing the MDF with a quick dry sealer to prep for painting. I then used a matte white spray paint on all the MDF parts. I decided to use a selection of varied materials and methods of manufacturing to give the Conductor texture. This ensured three dimensionality in the character's construction. The difference in weathering, damage, finish and colour all give the character a history that did not need to be explained explicitly within the play. During the play, the Conductor transforms part of itself to read a book and to serve tea. To implement this, I devised a method to hot swap the "shelf" section of the conductor during the performance. I began by 3D printing thin struts to span across the axle mounts with 4mm x 2mm holes to pressure fit neodymium magnets. These magnets are positively charged towards magnets that were pressure fit into the removable "shelves".

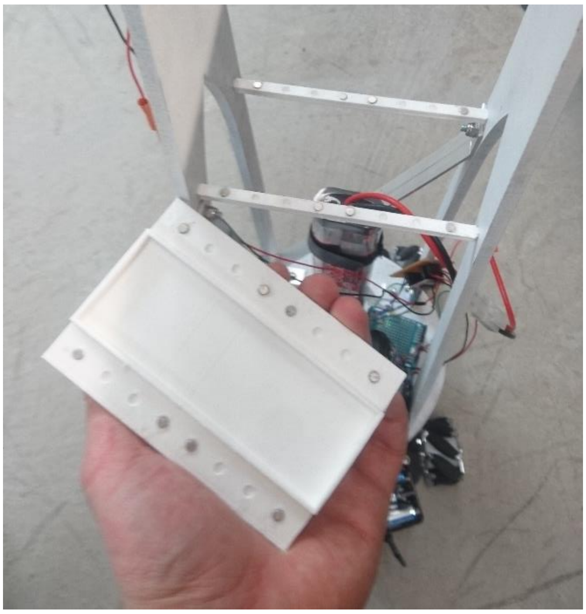

Figure 49: Blank "shelf" with magnets

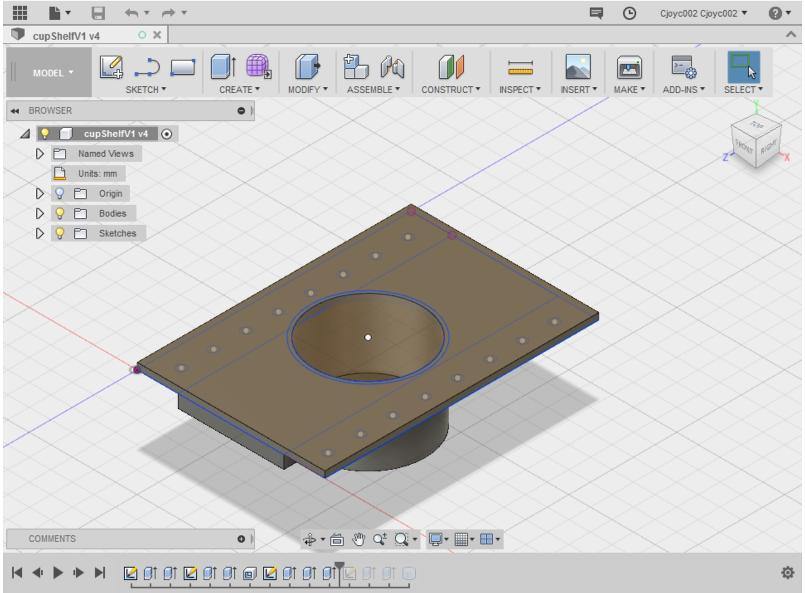

Figure 50: "Shelf" for holding tea cup

These “shelves” all have the magnet holes and are all extensions of the blank version in Fig.49. The book version in Fig. 52 sports two clear acrylic fingers that can hold a book in place with minimal pressure. The cup holder in Fig. 50 is for a scene in which the Conductor serves tea. The black side panels were modeled in Fusion 360 and printed on an Makerbot Z18 in one complete piece. They were attached with twist ties to allow easy removal as they both covered a couple bolt heads on each sode of the axle mounts. The front and back panels were screwed into place on their four corners with custom length screws in order to avoid damaging the MDF. The screw holes were sanded into with a dremel tool to allow the screws to sit flush with the surface of the acrylic. The front panel was engraved with the logo of the Conductor’s original manufacturer, “McCloud Security”.

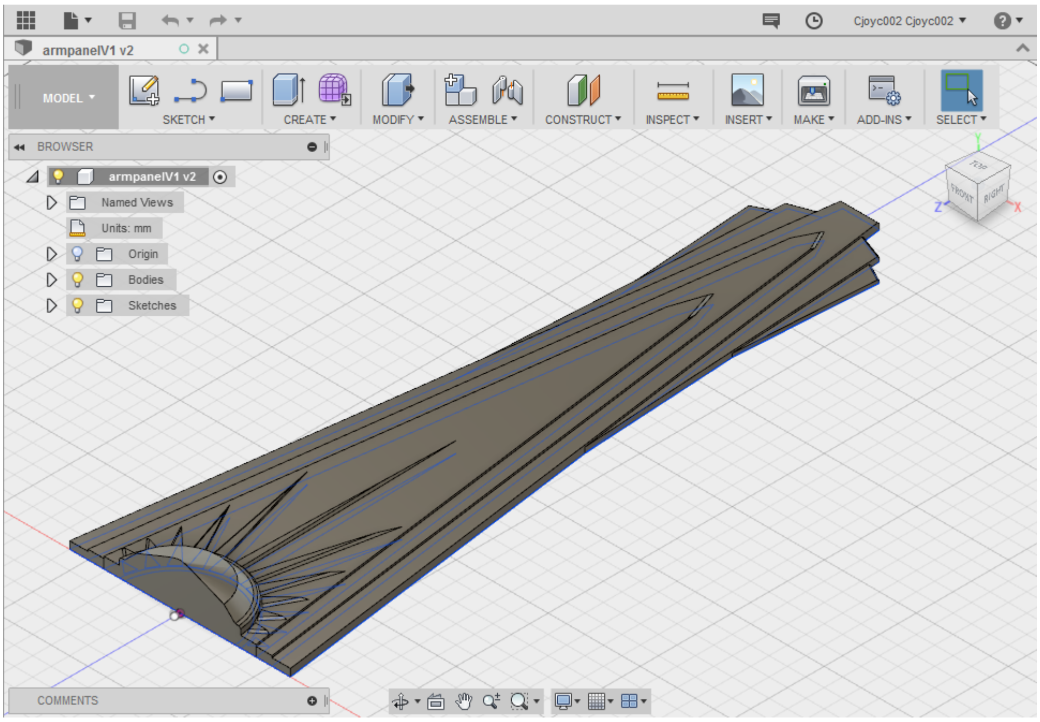

Figure 51: Side panel

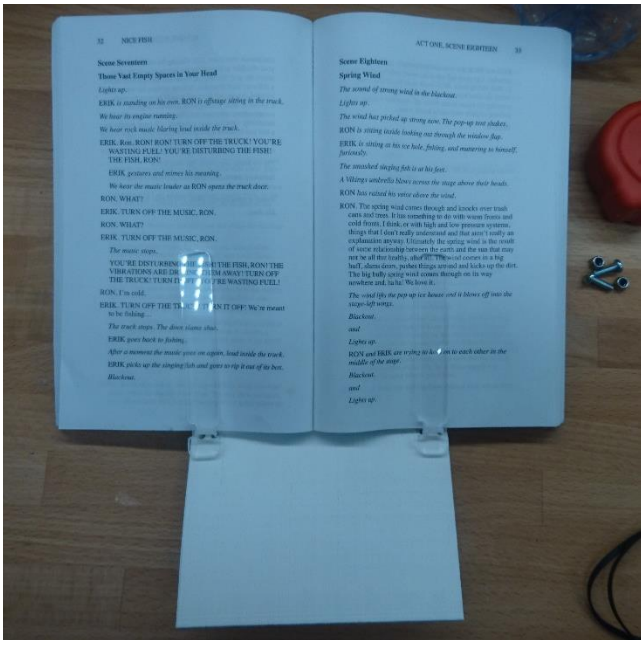

Figure 52: Book "shelf"

I changed the two sets of wires that are visible outside the body to vibrant colours. One set for the head assembly to the four AA batteries is orange and purple, and the other, which runs from the axle motor to the Arduino inside the body, is blue and red. This was an aesthetic choice to provide a hint of colour in the otherwise simple black and white tones, and to evoke the sense that the Conductor had replacement parts.

I inserted a small bluetooth speaker for voice cues and secured itto one of the metal struts with a ziptie.The final feature of the design is two vinyl decals, one showing the motor model and the other a warning symbold for the back panel of the body. With the wear and tear the finished parts have gotten during and since the final assembly, chipped paint, scratched acrylic and dirty wheels, I can happily say the character comes through as an outdated security drone that has spent many years on its own.

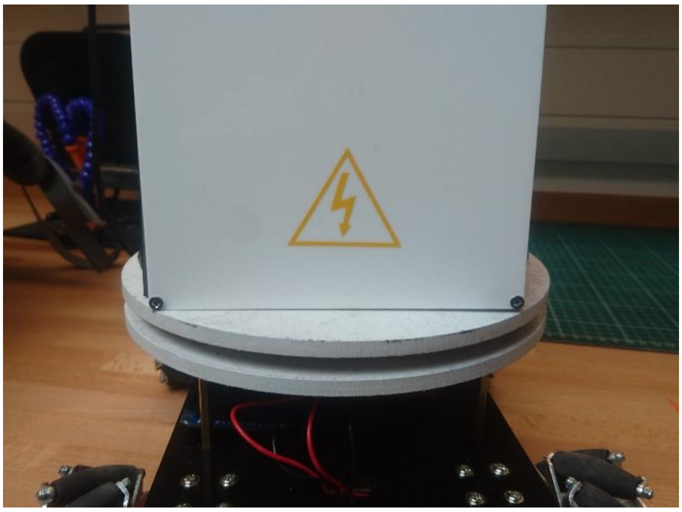

Figure 53: Warning symbol on back panel

Figure 54: The final construction

Control

Initial control system plan

My first design for the controller was a hybrid between a custom joystick for the platform movement and a custom controller for the movement of the body. The custom controller would be a small-scale version of the body and head assembly that would pivot on the same axes as its full-size counterpart. These axes would then be connected to a rotary encoder, and from there to an Arduino mini pro. The full-size animatronic would also need encoders fitted to the rotation of the motors. When installed, I would be able to use a PID controller to constantly calculate the error value between the position of the small-scale controller and the full size animatronic. That error value would be mapped to suit the scale between the two versions of the robot so that when the small-scale controller is moved, its large counterpart moves to the same position.

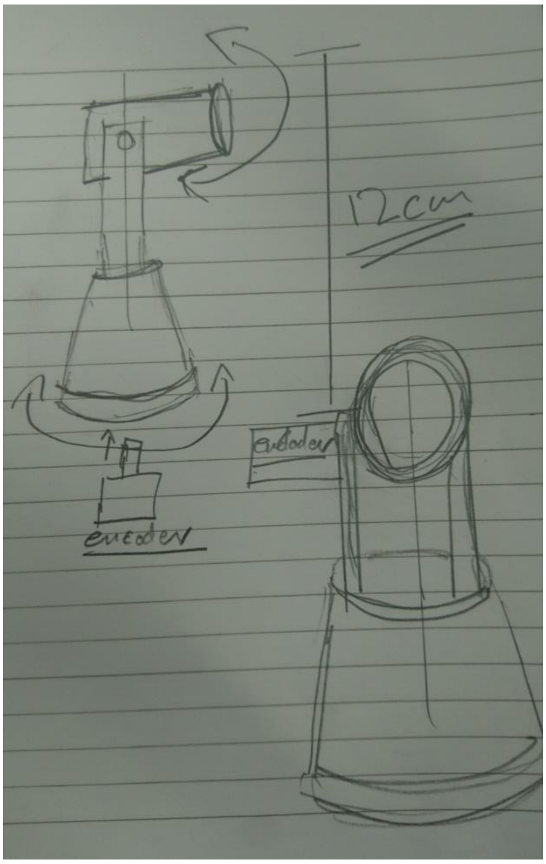

Figure 55: Controller Concept

Similarly, the full-scale version this model would be made with a combination of 3D printing and laser cutting parts. As the controller would only need to resemble the large-scale version it could be lightweight and highly portable. The electronics inside would consist of a similar construction to the head, a light-weight package of an Arduino Mini Pro, Xbee module and the encoders powered by one small bank of four AA batteries. With a switch to turn on and off the controller, the puppeteer would be able to use it in any configuration with the platform controls. The platform controls would be a separate module attached with the necessary wires. The module would use both a joystick and a directional pad to control the different movements of the platform (see Fig. 56).

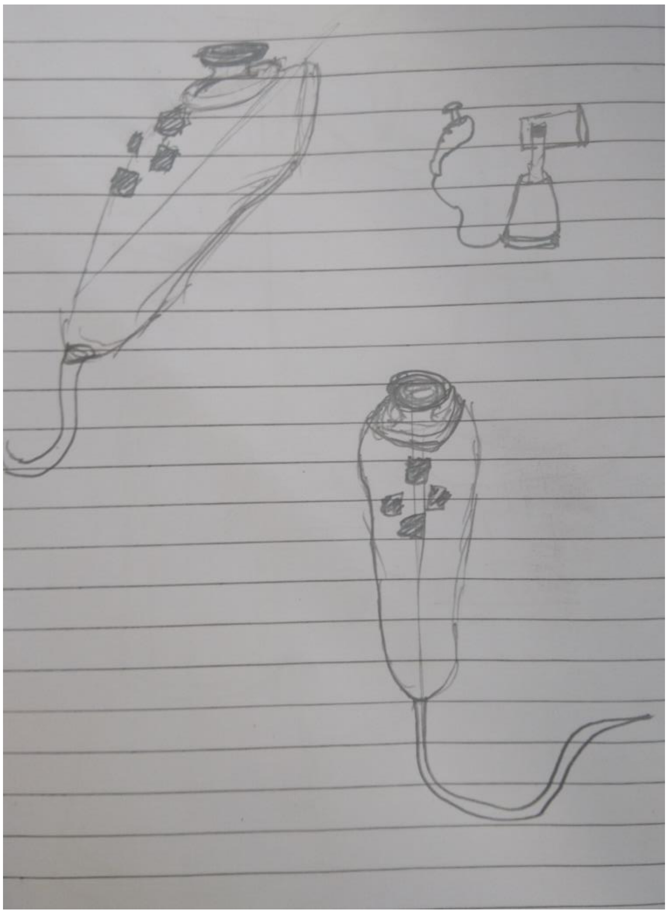

Figure 56

The four directional keys would be mapped to the rigid movement of the Conductor, forward, back, left and right, while the joystick would control the more fluid movements such as the spin left, spin right, diagonal left and diagonal right. The construction would consist of a 3D printed housing with the buttons and joystick inserted with wires running from both into the body controller. This design would be very ergonomic and perfect for right and left handed users.

Version used for performance

Due to time constraints, the controller used for the final performance was far more basic than the original concept. The controller was a byproduct of the original testing platform for the Xbee modules. A Processing program was written to connect to the COM port, to which the Xbee USB controller was connected. The program would then listen for any keystrokes on the host computer: if any keystroke matched a set parameter, the program would send a serial message to the COM port, thus sending it through the Xbee. The program is viewable in my code base [18]. The points of articulation and actions are mapped to specific keys, as seen below.

Platform key mapping

Key mapping	Action
Q	Spin anti-clockwise
W	Move forward
E	Spin clockwise
A	Strafe left
S	Move backwards
D	Strafe right

Body key mapping

Key mapping	Action
U	Eye colour pink
I	Head rotate anti-clockwise
O	Eye colour blue
P	Eye colour multi-colour
J	Body rotate anti-clockwise
K	Head rotate clockwise
L	Body rotate clockwise

18 Link to my Gitlab repository http://gitlab.doc.gold.ac.uk/cjoyc002/thirdYearProject

The voice cues are cued via a smart phone wirelessly connected to the Bluetooth speaker inserted into the body. The smart phone was outfitted with a custom playlist on the VLC media player. This playlist was played and paused by the puppeteer when needed. This is not a global solution, as Bluetooth has a relatively short connection range. With our small theatre space, we were able to conduct extensive tests and found there to be no area out of range. The act of playing and pausing was also a difficult operation, as the puppeteer needed to remove one of their hands from the keyboard to reach to the phone and then return to the keyboard with a chance of pressing the wrong keys.

These controls did work, but came with their own problems. Firstly, the platform, though the easiest to control, had inherent issues with misaligned wheels and would veer off course enough that the direction would need correcting regularly. The wheels do not have steering rods and to turn, the wheels must change direction entirely (see Fig.20). For example, when driving forward and making a left turn, the wheels must stop moving forward and spin to the left before continuing. This stop-and-start movement was not ideal as it slowed down the performance, as well as somewhat broke the illusion of autonomous, intelligent motion. Secondly, because of the lack of rotary encoders, the motors on the body were controlled by PWM alone; coupled with the inaccurate control of the keyboard, the head and body movement were based solely on the puppeteer's timing. Even with lengthy practice, the movement jerked from position to position, many times overshooting the intended mark. Finally, thirteen individual key bindings surrounded by other keys proved to be far too many and too confusing for a new user. Even after practice, the principle puppeteer had trouble pressing the correct keys. This control system was used as a patch for a gap that could not be adequately filled. However, even with its issues, it has brought up many alternative solutions, like the scale model controller.

Code

The code base, which is stored in my Gitlab repository, is written in two simple applications: Arduino IDE and Processing. These simple IDEs were chosen to demonstrate an accessible environment for amateurs to use. The control system, “controlProgV2”, as previously described, is written in Processing. This program opens a dialogue between two Xbee modules through a serial port and listens for key strokes on the user’s computer keyboard. When specific keys are pressed, a short “char” variable is sent over serial to the Conductor’s onboard Xbees. The keystrokes are recognized by the keyPressed() and keyReleased() functions, which each trigger individual boolean if statements. This configuration allows the puppeteer to simultaneously move multiple parts of the Conductor.

The Arduino IDE code is used strictly on the Conductor itself. The head program named “RGBLEDTest2” controls the RGB LED in the head of the Conductor. To connect with the control program, it opens a serial port to the same baud rate of 9600. The program first checks that the serial connection is receiving data, and then listens for “char” variables. Once one of the set variables are sent through, the light is changed to a preselected colour with the custom setColor() function. The setColour() function writes an analog value to the RGB LEDs pins for a specified brightness. In my case, I was using a “common anode” LED which turns on when the pin in question is in the LOW state.

The Arduino program for the body, “bodyCodeV1”, also opens a serial port and checks for data over the connection, then listens for specific variables. In addition I used the move() function that is designed to control the TB6612FNG motor driver. The TB6612FNG uses PWM to control the speed of the motor and digital pins to control the direction. The function starts with a simple if statement stating that if the motor equals 1, then the first motor’s pins are set to a given rotation and the speed is set to a given speed via PWM. If the there are no “char” variables being received, the motors are automatically stopped by enabling the motor driver’s standby pin, which cuts the power from the main batteries to the motors. The platform’s Arduino code is essentially the same as the body’s, but expanded to account for the number of motors.

I experimented with variable speed control, which, while possible and effective during tests, a finished speed control was not implemented for the performances. The speed was controlled easily due to it running on PWM, the issue, however, lay in the serial messages. For example, if the speed was reduced while moving forward and then the speed increased without stopping first, the system would be locked in its forward motion. When this happened, the only way to stop the motor would be to reset the Arduino itself by removing the power supply. After multiple test programs, I was unable to resolve the issue, I instead focused on the refinement of the single speed motions. The programs in my Gitlab repository are the same as those used during the performance.

Performance Evaluation

Puppeteering the Conductor

As the principle puppeteer, I accrued many hours of practice with the system. Over those hours, I made note of the engineering, design and programming from a purely performative perspective. I have not puppeteered something as complex before, and much of this analysis is from the perspective of a newcomer to puppetry. As an actor, the first steps I take are to ascertain the character's understanding of the world through their wants and needs. This approach led me to separate the "programmed" and the "un-programmed" sides of the Conductor. The "programmed" side was built to stand guard, interface politely with humans and to attend to all other station tasks. I knew that I could use this to my advantage by making use of the procedural paradigm and its queue-like approach to tasks. When the Conductor was "on duty" it would turn its eye blue and proceed to patrol the station, stopping and surveying the platform, and when a human arrived, it takes its place at the platform edge to wait for a train. While performing within this constraint, I found that the faults in my construction led to some undesirable effects. The connection between body and platform, as mentioned before, would loosen over time and cause the Conductor's body to rock back and forth, even when moving at an even pace in a straight line. Another side effect of my construction was the wheel alignment. The wheels are held to the motor shaft with a set of grub screws that would not always guarantee a perfectly straight rotational alignment with the body of the Conductor, and would cause the Conductor to turn lightly to the right. Due to of both of these issues, I was forced to correct with my puppetry in a way that I deemed to be out of character for the Conductor.

In its “un-programmed” state, the Conductor has a pink/red eye, and in this state the Conductor is as close to being “itself” and as “human” as possible. It scoots across the stage with agility and speed, without following its “on-duty” protocol. In this state, I was able to make use of the 360-degree rotation of the head and body, and the novel motion of the mecanum wheels. The Conductor could spin its body to signify happiness and perform its dance moves. It would spin its head in a full circle to catch the Fox spying on it, or to concur with the Human that “some people are just mad”. A fluke appeared in rehearsal; if the Conductor was unbalanced and spinning its platform on the spot and its body in the opposite direction, it would appear to skip in a circle. In reality, the weight of the head would unbalance the platform just enough to the point where one wheel would be lifted and lowered in sequence.

These observations have lead me to approach the design of this kind of system with a character more in mind. For much of the project I had focused on the aesthetics of the character and not what would enable it to express itself as it needed to. was Although I was able to perform each state adequately and was able to convey the character’s emotions, overall it was not nuanced as would be preferred.

Malfunctions

No performance is complete without problems on stage and off, I was lucky enough to only encounter one major malfunction twice. During the second performance, two of the AA batteries powering the platform’s Arduino Mega started to leak. Thankfully this occurred in the final act of the play while the Conductor was off stage, although an audible pop and splutter was heard from the audience. On immediate investigation, I realized it had to have been at least one of batteries, if not more. Needless to say, it was far too dangerous to continue performing with the Conductor. I proceeded to make it safe by disconnecting all power for each part of the system and carefully removing the guilty battery pack. As the play had very little time left, I stood in as the Conductor for the remaining scenes.

On later inspection, the malfunction was found to have been caused by a short in the circuitry caused by one of the battery cover mounting bolts. The offending circuit board, carrying the motor drivers, had come loose from its Velcro mount and moved to touch two of its soldered points to the head of the bolt. What I believe happened is that the power from the large 5000 mAh batteries was routed to the Arduino rather than the motors, and the voltage protection forced that electricity to the AA battery pack. I made the soldered connections safe with electrical tape and re attached the board to the platform. I discovered that the motor driver had also blown, and I replaced it easily due to my modular design. I began testing these adjustments by first turning on the Arduino Mega with nothing plugged in,and to my surprise it had survived. I continued testing by adding parts of its functionality back piece by piece. The Xbee continued working, receiving and sending serial messages with no trouble. I then attached the motor driver assembly circuit board, 6V batteries and the motors, and all continued functioning without any issues.

I understand that not only should I have made my circuit board safe by raising it clear of any metal and insulating the connections with either electrical tap or hot glue, but I also should have used diodes on my custom board. The TB6612FNG does not communicate with the Arduino, the Arduino sends signals to the TB6612FNG. To prevent this fault, I should have used a diode at every connection from the TB6612FNG to the Arduino to avoid any reversal in the current.

Project Evaluation

Audience comprehension

One half of this report investigates the affordability and accessibility of the animatronic, while the other half could be considered far more important: was it effective? The Conductor was attended by 90 people over its three-night run. To receive feedback on the play I wrote an anonymous survey[19] with the following questions:

[19] Link to my survey results - http://tinyurl.com/kcucx3z

Question No.	Question
1	What date did you attend the play?
2	In your opinion, did the puppet of the Conductor effectively convey the emotion of the character?
3	For the question above, why or why not?
4	What feature of the puppet was most expressive, eye, wheels etc... and why?
5	Is there a part of the design or construction of the puppet that detracted from the character?
6	If yes, could it be improved, added to or removed?
7	In your opinion, could the Conductor be played as effectively by a human?
8	For the question above, why or why not?
9	Do you have any additional comments?

Question 2 yielded an encouraging response; 85.7% of responders found the Conductor to be effective in its role while the other 14.3% found it partly effective. Question 3 revealed some more in-depth thoughts on why the character was effective to the audience. Within the 85.7% someone made the following comment on the projection of emotion:

> *By giving the bot characteristics and movement easily recognised by humans, such as the shaking to get attention, the audience is able to project emotion onto the object, as they are recognising the traits as human, and therefore can imagine what a human character would be feeling in a situation similar to the robots, making empathy easier. (Participant 18).*

The above comment highlights a key feature of my own investigation: can the projection of emotion from an audience or actor be as powerful a tool when utilizing a robotic puppet versus a traditional hand puppet. This sentiment seems to be true for more of the audience:

> *Despite only being articulated in a couple of places I thought that the puppet was very easy to connect to on an emotional level. Both the partial and full rotations of the "eye" effectively conveyed someone rolling their eyes, choosing to ignore something or pointing. I don't think a full gamut of emotion wood (sic) add to the value of the character. I also felt that I engaged with the conductor more than the other two characters in the story. (Participant 19).*

This certainly demonstrates that even with limited expression, the Conductor can hold the audience's focus during its scenes.

The other 14.3% were a somewhat more critical on its design, saying:

> *Had some good movements. Could do with more movements. Perhaps a more expressive eye. The light is nice but it could do with a more 'human' eye to make it relatable. (Participant 3).*

I agree with this comment completely, as I too felt as though the eye was rather lackluster: it had one function to control a light, which was far too simplistic and a small amount of articulation would have gone a long way. Another audience member stated:

> *The robot was sad were ambiguous (sic), sad was too similar to nothing. The puppet did convey well fear (from being touched), wonder (staring into the sky), happyness (sic) (dancing and shaking), curiosity. (Participant 7).*

From what I can tell, this responder believed that the sadness of the character was not conveyed as effectively as other thoughts and feelings, such as wonder and fear. I also noticed this during rehearsal, as there was no specific action that could telegraph sadness properly. We had tried looking down at the Conductors "feet", but ultimately that felt far to saccharine for the feeling of the play. We found that instead, the absence of movement was the better option for conveying sadness, as it juxtaposed both the peppy and happy spinning Conductor and the programmed, on-duty Conductor. I also ensured that, in order to signify a change of mood, the light change from a pink to a blue light was obvious, as if by choice the Conductor is returning to a state of mind it does not enjoy.

Question 4 was almost entirely dominated by the "eye" or the "face" of the conductor. Most of the surveyed audience was enamored by the Conductor's head and how it would move to react to the other characters on stage:

> *I think the most expressive feature of the puppet was the head. Its movement, especially when the puppet was sad or offended and was looking down, reminded me of young children when they don't yet know how to verbally express their emotions. (Participant 11).*

> *As a singular party, the eye as it is the most clear and recognisable human trait. However, as a whole, the fluid and thought through movement patterns, such as stopping and starting at the right moments and the dancing that had the greatest impact for me, and lead me to have the greatest emotional connection. (Participant 18).*

I felt the eye was the most expressive, being that it represents the conductors face. It was responsible for effectively communicating the characters reactions and emotions, and by and large did a good job of it. Despite the static body and simple articulation of the eye I thought that the wheels and the way the puppet was able to turn in gradients was an indication of the characters intelligence/technological sophistication in the story. (Participant 19).

That final piece of critique highlighted the other aspect of the Conductor in a way I had hoped from the start. As discussed in a previous chapter, the mecanum wheels were not only chosen as an effective solution for movement, but also as a source of the unexpected and the “out-of-the-ordinary”, which provided an element of the unknown in the play’s futuristic setting.

In Question 5, 71.4% said there was nothing that detracted from the character, while 28.6% said yes. Question 6 shed some light on the yes responses from the previous question. One responder said:

the noise of the wheels at some point disturbed me, even though it was bearable (Participant 5).

Another thought:

it would have been good if the head also moved side to side. (Participant 12).

Another astute audience member said:

It had no method of turning the pages of a book yet you still tried to convince the audience it reads. This invalidated the "intelligent", "reader" elements of the character conveyed through it's (sic) ability to recommend books to other characters. The use of sound in the robot disrupted my suspension of disbelief in the character as it's (sic) use wasn't consistent with my expectations. Why would it be able to play entire audio files but never use it practically? E.g. when getting other character attention. (Participant 7).

This is another comment I empathize with, as by the end of the project I had to cut features and also corners. In truth, the book “shelf” was a last minute solution. I had to rush through the final design as the initial plan couldn’t be addressed in time. I had plans for the “shelf” assembly to be a servo operated box. The closed state would be the Conductor’s normal working state. When opened, the lid would act as the book holder, and within the box assembly there would be a space for the tea cup to be held. I still have not formulated a solution to the problem of turning pages. I believe the sound from the conductor was an error from the script, which made it necessary for the Conductor to speak and play music. On reflection, it would have made sense to keep the Conductor entirely mute and for the station’s announcement system to be the sole source of sound. The Conductor would need to find another way to communicate that it reads, but that would be more realistic than filling in the gaps with lines. Having the Conductor speak in some ways devalued the meaning of its movement.

The audience was rather split on Question 7, "In your opinion, could the Conductor be played as effectively by a human?". 47.6% responded no, 28.6% said maybe and the other 23.8% responded with yes. In Question 8, almost every responder followed up their vote with a detailed response. Here is a selection of the comments from those who voted no, the Conductor could not be played as effectively by a human:

> *The fact that it was AI. It adds to the realism and the emotional weight of the character*
>
> *The relationship wouldn't have been the same. (Participant 9).*
>
> *A significant part of the relationship between the human actor and the robot seems to come from the robotic quality of the conductor. As the story progresses, they build an understand of one another. (Participant 2).*
>
> *It was the contrast of the two elements that made it more emotive. (Participant 16).*

Comments from those who voted yes, it could be better played by a human:

> *Because I perceived the conductor as a human. (Participant 17).*
>
> *Since on Saturday the Conductor broke down and Cormac took its place, Cormac was able to convey the emotions of what the conductor would have been feeling. Replacing the robot with a human just confirmed the emotions that I had thought the robot would have been feeling.*
> *Child actors. I don't think that the robot was able to convey enough of the emotional spectrum that the story of the play demanded. (Participant 15).*

From those who said maybe:

> *It would have to be done very sensitively due to the unavoidable and inherent creepiness of a commuter regularly stuck at a deserted railway station with a lonely person who is trying to block their phone signal. The robot diffuses this tension somewhat. (Participant 13).*
>
> *It would fundamentally alter the whole play so hard to imagine the comparison. (Participant 18).*

The survey proved very useful in either giving me inspiration on how to adapt and modify the current Conductor or to refactor the play, while also confirming my own suspicions about how the design and construction failed in some places. I knew that some things would not get past the audience, such as the reduced mobility and the array of "shelves". I also received great feedback on the play itself, what worked and what did not. After this experience and taking on board the feedback I received, I feel far better equipped for the process of integrating robotic elements into theatre in future.

Further development of puppet

During the project, I had to make design choices that would impact every part of the character, and some of those choices fell flat. It took seeing the final production come together and hearing from the audience to realize some of changes that could be made. With all their help, I believe that a second and more effective version of the Conductor is possible, and this is how I would achieve it.

I would first change the motor system in the body. I loved the low profile and high torque of the geared DC motors, but as mentioned before, they were non-programmable and not precise. I would begin by either adding rotary encoders or replacing the system with motors that had in built encoders. Encoders are not as precise as Servos or stepper motors, but the benefits outweigh the precision. DC motors are far less expensive, need less current for their relative holding torque compared to a stepper motor and most importantly for the Conductor, they can revolve freely, unlike a Servo. On top of those benefits, the motors would be programmable, which would not only allow for better control but the potential for automation.

The "shelf" assembly never felt right being changed without any hint of how it was controlled by the Conductor. I would redesign that whole assembly to fit organically and to operate automatically, either by the control of the puppeteer or by being programmed in. The book holder could potentially be a lid that can be opened and closed, with a small embedded Servo motor and under the lid with a cut out for the teacup. I would also need to figure out a way to make the Conductor look like it can turn pages.

In addition to not being able to turn the pages of its book, the Conductor did not use its voice very effectively. I believe that it was a scripting and staging error which led me to have the Conductor speak and play songs. I would either keep the Conductor mute through the whole production, or have the Conductor be vocal in a more consistent manner. In terms of the tea, I will need to decide on if the Conductor fabricates the tea within itself, or if it transfers a cup into its cup holder. Both considerations would require a revision of the script itself so that the conventions are set in stone from the very start of the production.

Once the changes to the motors and other conventions are made I would move onto refining the overall movement. Currently the movement is somewhat slow and jerky, making the body overshoot its marks, requiring correction. This is also in part due to the weight balance between the head and the battery pack. They are both on either side of the axle to each other, but if corrected, a smoother motion could be achieved. The platform could be more effective if less linear in its direction. If the custom controller is a success, I would be able to map the platform's direction to the joystick, stopping the puppeteer from using a complex set of keys. In addition to being less unwieldly in the second version, I would make sure that speed was a variable factor. Both the platform and the body would benefit greatly from moving as different speeds. The Conductor would be able to communicate things such as caution, sadness, wonder and its inquisitive nature far more effectively.

Outreach to theatre community

After finishing the Conductor, I believe that this process can be applied to other independent and small budget theatre and film projects. The technical barrier is certainly there, but with the tools that I used either for free or at low cost, even the most amateur of productions could be able to create similar animatronics. In terms of cost, the components for a character similar to the Conductor are only a fraction of the price compared to anything being used now in the field. I intend to proclaim the benefits of this approach to effective and low cost robotics on stage to the theatre and film community at large. I will publish my build log with the components, price list and code that went into the project, as well as the resources and tools I used to teach myself. as Additionally, the final production was filmed and will be released as a companion for the build log, to demonstrate and contextualize the design choices made for the Conductor. In order to make my work available, I will create a dedicated space for the project to live with the resources readily available on platforms like Github and Thingiverse. This dedicated space will also serve as a space for any future additions or modifications to the Conductor, and any new projects that explore robotics on stage and in film.

In terms of reaching out to the community, I want to begin by approaching Les Enfants Terribles and other theatre companies who share a passion for using puppetry and new technology in theatre. I think this project would benefit from a perspective on how the process can be integrated into a professional production in terms of finance and time constraints, and tailored to the creative needs of the entire production team. I want to be able to speak to independent companies with the upmost confidence that my approach can work for their production. Furthermore, this entire project has been a valuable lesson on how technology can work with a historically non-technological collaborative medium, a lesson that has inspired me to continue working with new technologies in a creative capacity within theatre and film.

Conclusion

With this project, I intended the robotics, design and the play to serve as a proof of concept to illustrate my hypothesis that fully fledged animatronic characters are affordable, possible and effective in theatre of any size. This was never intended to be a finished product that would require no adjustments. After reading the audience feedback and comparing the performances to other plays with robotics, I argue that my hypothesis is true. The Conductor's history is conveyed through its design and its weathered appearance, it speaks through the motion of its unpredictable articulation, showing the audience a character that is at ease with its life and excited for new experiences. The audience connects with its gaze and the care it took in its job and the attention it payed to its friends. This is a truly three-dimensional character that adds to the immersion of the production.

Much has changed in the past eleven years since *Heddatron*: electronics are cheaper, educational resources have taken root in the community and makerspaces have enabled anyone who wants to create to begin building. My final build cost came to £482.26, which compared to the market of Robothespians and autonomous singing robots (which can range all the way up to £50,000) is very affordable. Even after the cost, the most effective projects have partnerships with a world-renowned robotics research labs in Japan and Germany. However, now that applications and software are available largely for free, the world of robotics is increasingly becoming more accessible. It will take communication with theatre community to introduce them to the methods demonstrated in my project. With time, I believe that theatre companies will see the potential in developing animatronics for their productions and we will see more fantastic works like *Heddatron, Robots, My Square Lady, I, Worker* and *Sayonara* come to fruition. If a character like the Conductor can come to life by way of a student's budget and resources I can only imagine the possibilities of a production that invests time, money and the full creative might of a theatre company into a Conductor of their own.

Appendix

Code

www.gitlab.doc.gold.ac.uk/cjoyc002/thirdYearProject

Script

www.gitlab.doc.gold.ac.uk/cjoyc002/thirdYearProject/tree/master/script

Audience Survey

tinyurl.com/kcucx3z

Components List

This is a complete list of the electronic and mechanical parts used in the final build. This does not include Wood, 3D prints, fittings, acrylic, test parts or use of tools.

Name	Quantity	Use	Cost per item (at time of writing)
Arduino Uno imitation	1	To control the body	£6.95
Arduino Mini Pro imitation	1	To control the eye	£3.99
Arduino Mega 2560 imitation	1	To control the Platform	£12.00
Sparkfun TB6612FNG	3	motor control	£6.38
Matrix board 10cm x 5cm	1	custom circuit boards	£2.75
25GA-370 DC motor	4	Mecanum wheel	£12.35

		rotation	
60mm Mecanum Wheel	4	Platform movement	£21.41
100mm square Bearing	1	Connection stability	£4.50
6mm Bore mounting hub	1	Hub for body to platform motor.	£7.39
Zheng ZWL-FP100 DC motor	2	Body and head rotation	£13.74
12V 5000mAh NiMH battery	1	Power for body	£43.80
6V 5000mAh NiMH battery	2	Power for platform	£21.40
Xbee series 1 module	4	Communication between controller and system	£26.90
Xbee breakout board	1	For eye circuit board	£5.21
Xbee USB Explorer	1	To attach Xbee to controller	£14.20
Xbee Arduino Shield	2	For modularity	£14.26
8mm timing pulley	2	For head rotation	£1.72
Timing belt	1	For head rotation	£6.37
6 x AA battery housing	2	For platform and body Arduino power	£2.49
4 x AA battery housing	1	For eye Arduino power	£1.99

Male battery clip	3	To connect batteries to circuitry	£1.37
Total			£482.26

Software used

Autodesk Fusion 360. Free. 3D modeling - www.autodesk.com/products/fusion-360

Inkscape. Free. Vector drawings – www.inkscape.org

Autodesk Eagle. Free. Circuit schematics - www.autodesk.com/products/eagle

Cura. Free. 3D printer slicing for Ultimakers – www.ultimaker.com/en/products/cura-software

Makerbot Print. Free. 3D printer slicing for Makerbots - www.makerbot.com/print/

Arduino IDE. Free. IDE for Arduino boards - www.arduino.cc/en/main/software

Processing. Free. IDE for controller - www.processing.org

XCTU. Free. Xbee configuration - www.digi.com/products/xbee-rf-solutions/xctu-software/xctu

Online resources

Github. Opensource projects and programming community - https://github.com/

The Maker Map. A map of maker spaces around the world – www.themakermap.com

Thingiverse. Open source 3D printable models - www.thingiverse.com

Circuits.io. Easy online circuit diagrams - www.circuits.io

Stack Overflow. Programming forum - www.stackoverflow.com

The Nature of Code. Processing tutorial – www.natureofcode.com

507 Mechanical Movements. Mechanical engineering concepts - www.507movements.com

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