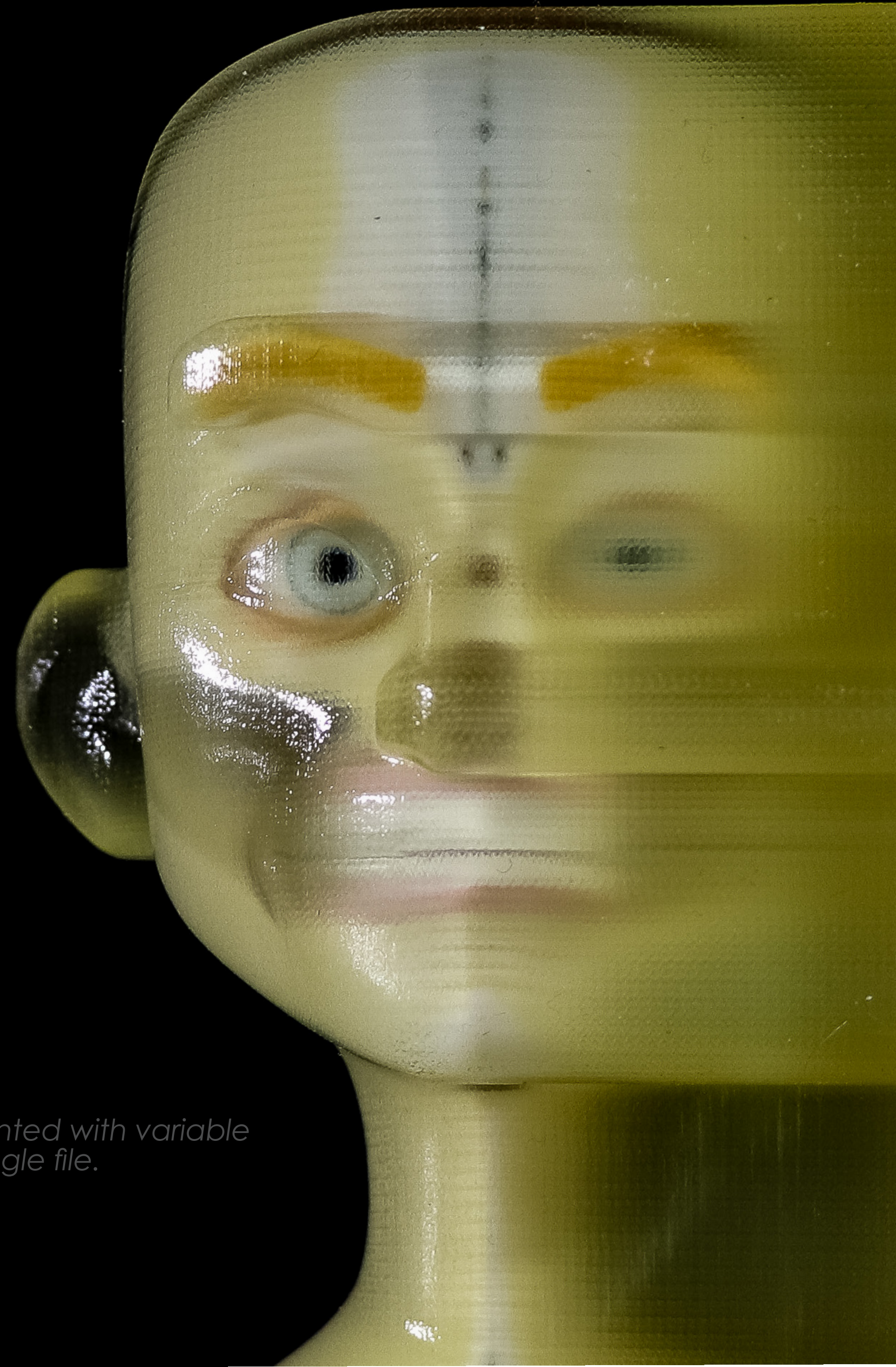
Callum Loughnan
2022

Printing Puppets.



Meet Jeffrey.

The pre-assembled mechanically posed stop-motion puppet head. 3D printed with variable part density afforded by Multi-Material Poly-Jet printing technology in a single file.

Printing Puppets.

Meet Jeffrey.

The pre-assembled mechanically posed stop-motion puppet head. 3D printed with variable part desity afforded by Multi-Material Poly-Jet printing technology in a single file.

This is a ninety-point thesis submitted to the Victoria University of Wellington in partial fulfilment of the requirements for the degree of Master of Design Innovation in Industrial Design.

by

Callum Loughnan

Victoria University of Wellington School of Design 2022

Supervised by Ross Stevens

Cover: Figure 1: Jeffrey in support #1

ACKNOWLEDGMENTS.

I would like to thank my supervisor Ross Stevens, for all of your fantastic guidance and kind words in support of my unorthodox research.

Thank you to the MADE and NZ Product Accelerator groups for funding my research and making this research possible.

Thank you, Phil Jarrett, the university's Poly-jet print technician for your help and advice.

Thank you to my parents, Karen and Gary, for your continued love and support throughout my studies and beyond.

And a huge thank you to Sophia, Andrew, Timmy, Izzy and Charlie. Your support and endless laughs offering a great work environment to be a part of.

Figure 2: Sketch #1

AUTHOR'S NOTE.

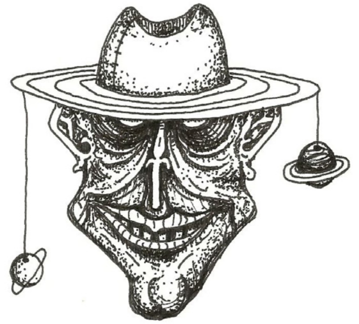


Figure 3: Sketch #2

This research is conducted as proof of concept, testing the ability of current 3D print technology to create pre-assembled complex mechanisms of variable part density in one print file, afforded by the operation and material qualities it uses. The context is chosen due to having long been interested in stop-motion character animation, and for as long as I can remember, I have been fascinated by faces and the stories they can tell, sketching and doodling characters throughout my life. I have no background in the area of mechanics or engineering but have always found it interesting and saw this research as an opportunity to explore using my background in industrial design and 3D modelling/printing.

Figure 4: Sketch #4

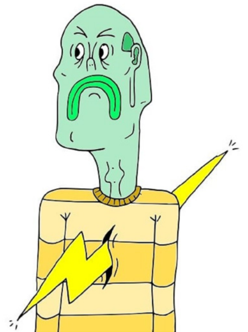


Figure 5: Sketch #3

ABSTRACT.

Stop Motion (SM) Animation has been around almost as long as photography itself, finding its home in recent years in stylised character films, taking advantage of its unique visual qualities as a tool to tell their stories. Facial animation however, has been a complex part of the process due to the intricacy of facial expression. Two methods I have seen executed effectively are the 3D printed replacement methods seen in films from Laika Studios and the mechanical positioning of faces seen in Corpse Bride, directed by Tim Burton. SM replacement animation requires a different version of the object being animated to be swapped out for each frame of shape change. So in the case of Laika's feature-length films, this results in thousands of expensive, non-biodegradable faces being printed, some only being seen for 1/24th of a second. In Corpse Bride, the main characters' faces are animated through mechanically shifting silicone faces, incrementally posed between frames. An effective way to animate using a single puppet, but to create these puppets requires hours of highly specialised artisans from engineers to sculptors to mould makers and painters, (Mackinnon & Saunders Ltd, 2005). The aim of this thesis is to find out if the mechanical one puppet method can be achieved by exploiting the full capabilities of the 3D printing technology used by Lakia. Full capabilities in respect to the accuracy, variation of material colour and flexibility, and with the use of degradable support, can be manufactured pre-assembled, requiring only a single step of physical manufacture. Advantages of which could make SM facial animation more accessible to storytellers keen to use its unique visual qualities and open up further exploration into other implementations of this production method in the area of pre-assembled mechanics.

CONTENTS.

INTRODUCTION.

Stop-motion animation is the process of photographing real objects and characters posed incrementally. When played as video frames, the positional changes in the photos create an illusion of independent movement, bringing inanimate objects and puppets to life, (Maselli, 2018). Stop-motion was first exibited in 'Humpty Dumpty Circus' made in 1897, (Maselli, 2018). Early use of it was implemented in early visual effects, seen to bring King Kong to life in 1933's King Kong, (Maselli, 2018).

My interest in stop-motion started with exposure to claymation used in Pingu and Wallace & Grommit, along with feature-length films such as Tim Burton's Corpse Bride and Wes Anderson's Fantastic Mr Fox, which use poseable armature puppets. The physicality of the sets and characters illuminated by real lights bring a depth, and distinct visual quality described as, 'a unique form of fantasy that is difficult to analyse because it provides an atmosphere of a dream world rather than a fake reality', (Yekti, 2015) when compared to other forms of animation. My interest grew in discovering the immense work required to produce these animations, with scenes posed and photographed 24 times to produce a single second of moving footage. Stop-motion production has developed with technological advancement in recent years, redefining what is possible in this age-old art form.

This research aims to push the capabilities of some of the latest 3D printing technologies, attempting to produce complex, pre-assembled mechanisms, including parts of varying density/flexibility, printed in a single file. The function of these mechanisms are tested in the context of stop-motion facial animation, inspired by award-winning developments in this area of expertise.

RESEARCH QUESTION.

Can complex functional mechanisms consisting of parts with varying densities be 3D printed, pre-assembled in a single digital file, and tested in the context of repeatable and reversible posing of a puppet head suitable for SM animation?

...Can a single 3D print be brought to life?

Figure 6: Jeffrey Blender Screenshot #1

1

METHODOLOGY.

This chapter describes and justifies the method of design research in which this research is conducted and lays out its aims and objectives, identifying the direction of the research.

Objectives of aim one are conducted through background research, and objectives of aim 2 are conducted through experimentation and the final application of Jeffery.

METHODOLOGY .

RESEARCH THROUGH DESIGN.

Iterative design experimentation is completed through targeted 3D test print experiments. These experiments test the material characteristics and capabilities of Ploy-jet printing and the functionality of the designed mechanisms they produce. Experiments are then tested and redesigned according to the level of success in their intended function, attempting to correct any complications that result in failed or ineffective function. This process is an example of research through design, a research methodology that targets the refinement of a design output afforded by the knowledge acquired through iterative testing. As stated by Anne Burdick, cited by (Frankel & Racine, 2010), "research through design recognises the design process as a legitimate research activity, examining the tools and processes of design thinking and making within the design project, bridging theory and building knowledge to enhance design practices.".

AIMS AND OBJECTIVES .

Aim 1

Investigate current methods of stop-motion facial animation and discover what articulation is required to represent a range of expressions.

Objective 1a

Analyse examples of current SM facial animation methods as well as how they are manufactured and posed.

Objective 1b

Discover what individual facial movements are combined to create a range of expression representations.

Aim 2

Through experimentation, test MMP ability in the context of a mechanically posed flexible face.

Objective 2a

Test Poly jet printing's ability to print pre-assembled mechanical systems.

Objective 2b

Test the performance of flexible material when the face is stretched and deformed when posed.

Objective 2c

Print full head with a range of different independent facial articulations capable of incremental posing.

2

BACKGROUND RESEARCH.

This chapter shows background research conducted in the industry of the desired output and methods of making used in this research. This gives context to the research and offers insight into the possibilities of design outputs.

2.1

MULTI - MATERIAL PRINTING.

This section explains how the 3D printer, used to produce outputs and material tests functions, explores the properties of materials used and how it builds its prints, showing insight into how it can be used in the research context.

J850 POLY-JET PRINTING

The 3D printer used in this research is the Stratasys J850 Poly-jet 3D printer, which is capable of Multi-Material Printing (MMP). It is operated at the Victoria University of Wellington Architecture and Design Campus.

How it works

Digital 3D files are prepared in Grabcad Print where characteristics of parts are assigned and sent to the printer. The J850 builds its parts by placing tiny droplets of UV resin manufactured by Stratasys at a resolution of 300 x 600 DPI in layers that are instantaneously cured by UV light. Their thickness of these makes them voxels, a pixel's 3D equivalent. The printer can use seven resins of different characteristics simultatiousely while building parts. Different parts of a 3D assembly can be assigned with different materials and combinations of materials, hence Multi-Material.

The Materials

Vero
Vero resins, when cured, are rigid. The Vero resins included in the printer are magenta, cyan, yellow, white, black and clear. The combination of these resins offers full-spectrum colour printing. These resins, however, do not mix when printed. Voxels are placed in orientations that, because of their size of down to 14 microns, give an appearance of different colours. Vero material is used in this research for its rigid composition suited to the precision needed for gears and mechanisms, as well as colour capabilities.

Agilus
Agilus, the seventh resin of the university's printer, when cured, is flexible and clear translucent. It is printed in the shapes of the 3D file, but after cleaning the part, it can be deformed and stretched, returning back to its original shape. Agilus material is used for the deforming of the puppet's face to mimic the morphable structure of our own.

Support material
SUP706 Support material encases the printed parts allowing them to be built as they appear in the file. It is a gelatinous materialthat crumbles and is helped along by warm water when cleaning. This material, along with the accuarcy of the printer seperates moving parts from other components.

2.2

PRECEDENT REVIEW.

This section provides analysis and explanation of precedents chosen for their advancement in SM facial animation are conducted, examining what is possible at the highest level in this area of expertise. The advantages and disadvantages of both are highlighted, resulting in an output goal.

PROCESS AWARDS .

Mackinnon & Saunders

In 2006, Ian Mackinnon and Peter Saunders were awarded the Ub Iwerks Award at the ASIFA 33rd Annual Annie Awards in Hollywood. This Special Jury Prize for Technical Achievement honours the ingeniously machined face controls designed especially for Corpse Bride.

(Mackinnon & Saunders Ltd, 2022)

Laika Studios

In 2016, Brian McLean and Martin Meunier received the Scientific and Engineering Award , presented an the Academy Awards, for Laika's pioneering use of rapid prototyping for character animation in stop-motion film production.

(Mike Goroway, 2016)

LAIKA STUDIOS 3D PRINT REPLACEMENT .

Laika Studios is an North American-based SM animation studio responsible for films such as Coraline, Paranorman and Kubo and the Two Strings. They use a process called Replacement Animation to animate the faces of their characters. This method sees the creation of separate 3D face frames of deformation that are replaced frame by frame on the poseable body. With every change in shape, a different face frame has to be seamlessly swapped to create the illusion of a morphing face that is very much solid in its construction, (Maselli, 2018). The same method was implemented in Tim Burton's The Nightmare Before Christmas, where each change in expression was hand-sculpted/painted, and heads replaced in order, (Maselli, 2018). Laika's process is different because they CG animate character faceplates in software such as Maya, then export the digital frames to be 3D Printed and replaced on the puppet's head, (Brian Mclean, 2016).

Advantages

Advantages of this process include a reduction in production time compared to its hand-crafted counterpart. This process also allows a broader range of expression and increases accuracy in its morph due to digital control and print accuracy. In addition, more recent films such as Kubo and the Two strings and The Missing Link used the Stratasys J750's ability to embed colour to the printed frames, further decreasing production steps. Also, with the consistency of digital manufacture, parts can easily and quickly be duplicated if missing or damaged. Another advantage of this workflow is the ability to trial different iterations digitally without the necessity of construction to visualize a possible output, endlessly tweakable until the final stage of printing.

Disadvantages

The downsides of this method are that each shape change requires an entirely new face plate, along with every frame in between. This results in vast quantities of faces being printed, some only being seen in the film for 1/24th of a second, 24 frames a second being the frame rate widely used in SM productions. These frames are made up of layers of resin that are not biodegradable, and because of the complex colouring and UV curing process of the J750, the material cannot be recycled either. Only reusable if the exact frame of expression is again needed. This 3D printer is highly specialized, and printing can be expensive compared to others, so these large batches of prints can result in high material and operation costs. In addition, the pre-determination of the printed expressions restricts animators from altering the puppet's performance during production.

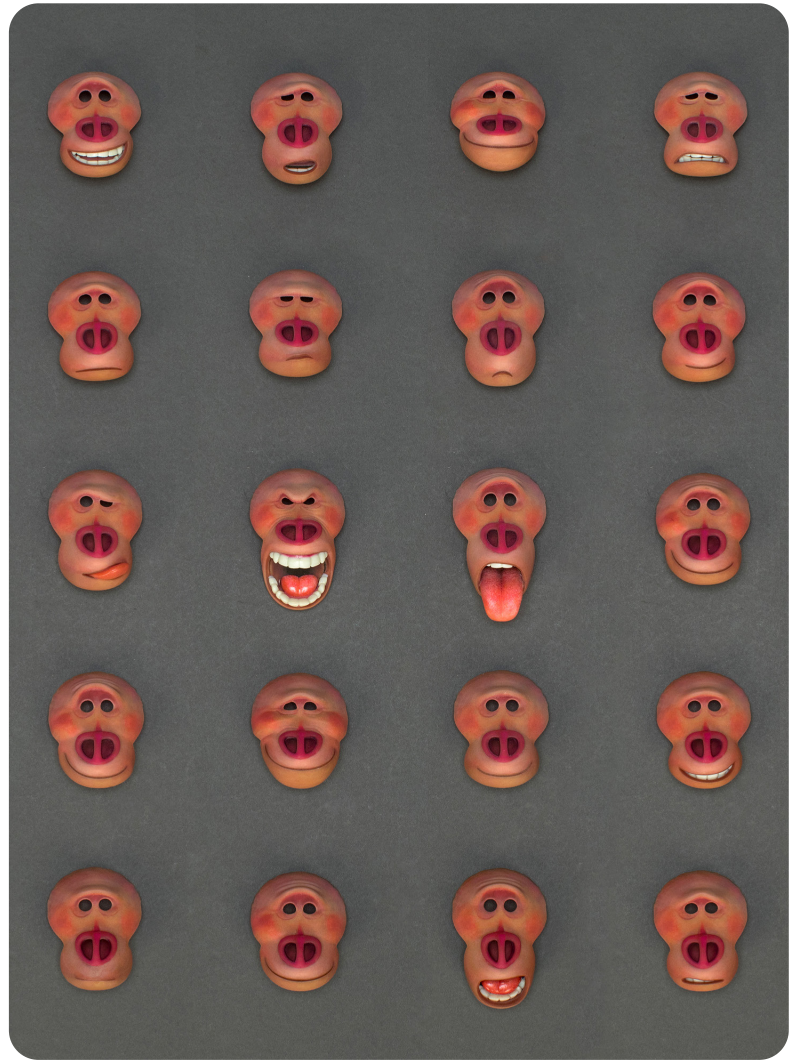


Figure 8: Mr. Link's different faces and emotions were 3D-printed with the patented Cuttlefish technology of Fraunhofer IGD. (LAIKA Studios, 2019)

MACKINNON & SAUNDERS MECHANICAL POSE .

Another form of SM facial animation is a mechanically posed puppet head. This method is used in Tim Burton's Corpse Bride. The puppets, designed and manufactured by Mackinnon & Saunders a UK based SM studio, they feature a soft silicone face that is morphed incrementally and posed between frames with the use of internal gears shifting positions of the brow, jaw, and corners of the mouth. In addition, the eyes are animated through replacement (Mackinnon & Saunders Ltd, 2005).

Advantages

This method offers repeatable facial animation with a single puppet head and its materials. In contrast to the predetermined replacement method, the animators can perform with more flexibility, having the ability to alter the character's demeanour, adjusting to the setting or situation if they choose to do so.

Disadvantages

A downside of this method lies in the construction of the puppet head. In contrast to Laika's digital creation, every step of its production is hand-crafted, from the sculpting, casting and painting of the head to the assembly of the 'swiss watch' like mechanics and the mechanisms they drive. After which, animators are left with a singular puppet head. Though the face is animated with a single puppet head, multiple duplications were made during Corpse Bride's production to keep up with wear and tear. So with every new head, the assembly had to start from scratch, with extra attention to detail being required to avoid the duplicates

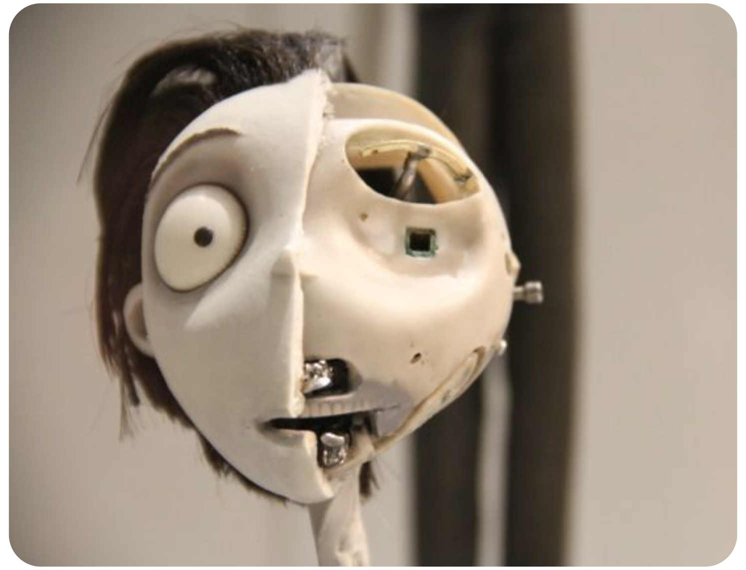


Figure 9: Victor Van Dort Puppet head, (Mackinnon & Saunders, 2005)

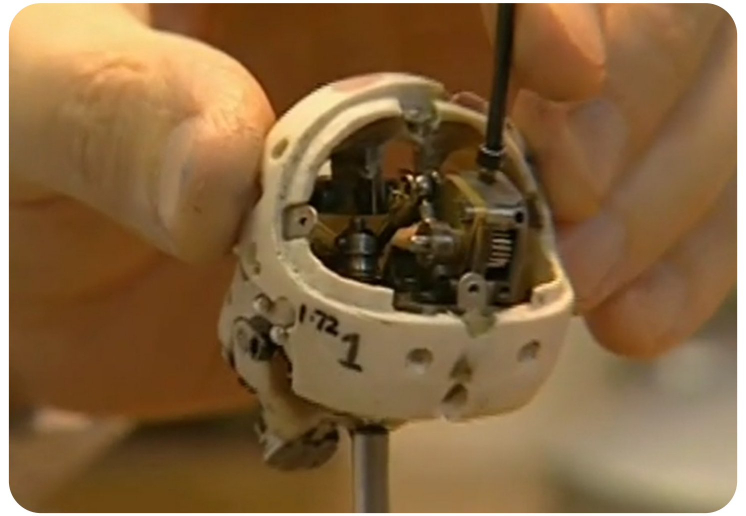


Figure 10: Corpse Bride Puppet head, (Mackinnon & Saunders, 2005)

OUTPUT GOAL .

The output goal of this research is to produce a mechanically posed puppet head inspired by Mackinnon & Saunders Corpse Bride design but instead produced through the digital design and manufacture methods exhibited by Laika Studios, combining advantages of both methods.

3D printed in one file on the Stratasys J850 Poly-jet printer. This print aims to feature pre-assembled gears and mechanics to incrementally and independently pose portions of the face to create a wide range of expressions suitable to be SM animated. This puppet also aims to include flexible, deformable skin using the Agilus material and coloured rigid components using Vero materials.

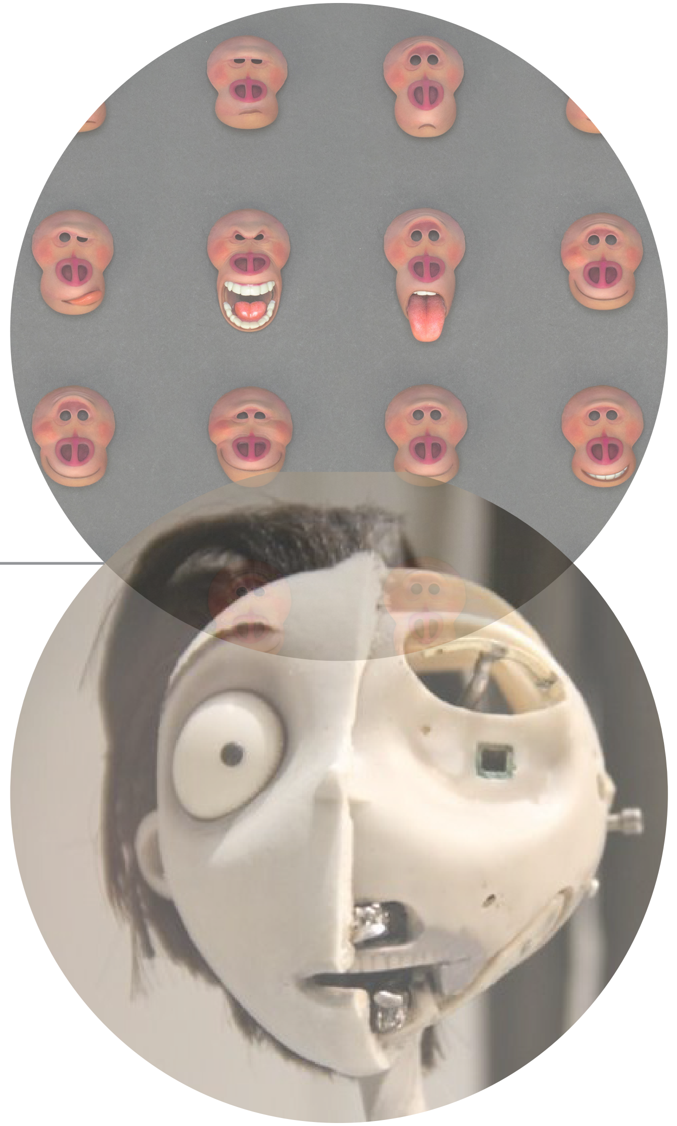


Figure 12: Jeffrey Blender Screenshot #3

3

EXPERIMENTATION.

Through ideation and a range of design software, this chapter develops digital material and mechanism experiments to be printed on the J850. Experiments are tested and files altered based on performance, This knowledge is then applied in the formulation of the final design output.

3.1

SKETCHING MOVEMENT.

This section shows sketches produced in an attempt to speculate how individual movements of the face may be articulated. Movements are chosen based on their use in the seven universal facial expressions of emotion.

MOVEMENT CHOICE .

A facial expression is the individual movement of facial components that, in different combinations, can be read by an observer to be signalling emotion. These movements are shown in the seven universal facial expressions of emotion (happiness, surprise, contempt, sadness, fear, disgust and anger). These expressions consist of different positional changes of the eyes, eyelids, brow, mouth and nose, (Matsumoto & Ekman, 2008). With these movements in mind, rough sketches were made identifying the areas of the face to move, how movements may be conducted using digital materials, as well as possible gears to drive them.

IDEATION SKETCHING .

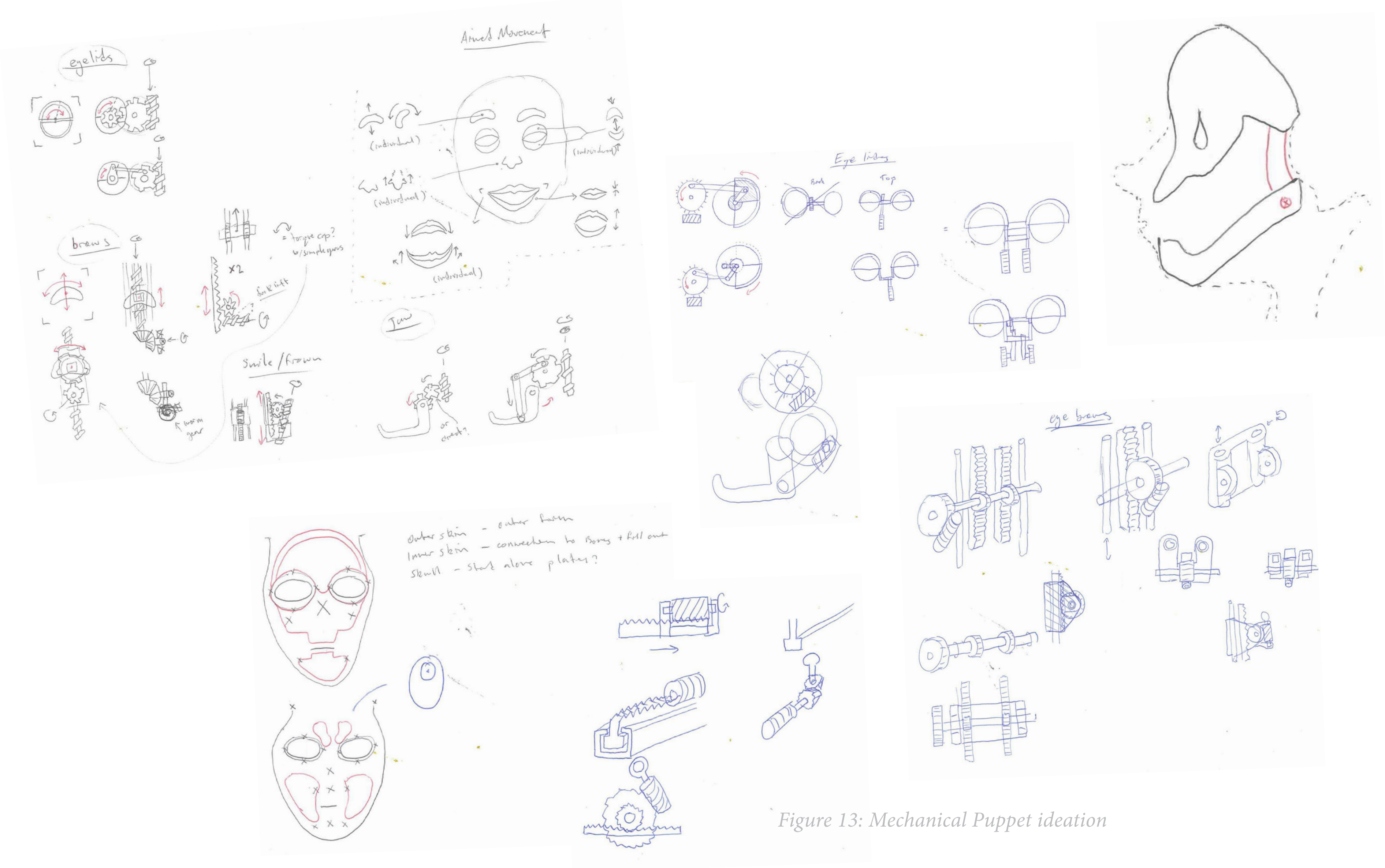


Figure 13: Mechanical Puppet ideation

3.2

SOFTWARE & 3D PRINTING PROCESS.

Detailed in this section is the 3D modelling software used to produce the digital parts destined to be printed, alongside the process involved in the use of the J850.

DESIGN SOFTWARE .

Fusion 360

Fusion 360 is a 3D modelling software offered by Autodesk. The 3D files it produces are exportable for digital manufacture. Often used for engineering purposes, this program is used to source and initially position gear assemblies and gear test supports.

Blender

Blender is an open-source computer graphics and modelling software often used for 3D animation and visual effects, 3D models are also exportable for digital manufacture. This software is also used for part modelling, especially those that are character-related, offering more control and methods of editing the 3D files. The ability to simulate the movement of the gears and mechanisms also allowed the ability to identify and avoid possible part collisions when in operation.

3D PRINTING PROCESS .

GrabCad Print

Grabcad print is a 3D printing software used to convert files from modelling softwares into files that printers read to manufacture parts. In the case of the J850, this is where the colour and material flexibility are assigned.

Printing

The Grabcad file is then sent to the campus's Poly-jet technician to print on the J850.

Cleaning

While wearing gloves due to the support material's mild corrosive qualities it can have on the skin with prolonged exposure, toothpicks and bamboo skewers are used to break up support material surrounding the resin parts, soaking and rinsing the parts with warm water to help degrade its structure. A toothbrush is used to scrub the remaining residual material from its surface. The use of the pressure washer is avoided due to the fragility of small parts, as well as the use of a chemical bath recommended by the university's Poly-jet technician when dealing with thin-walled Agilus.

3.3

MATERIAL & MECHANISM TESTING.

Included in this section are the 3D design and printing of targeted material and mechanisms experiments, testing of which gauges the success of their desired function, and if of great enough disfunction, they are then remodelled and re-tested to minimise issues hindering it. This design phase highlights the material capabilities of the printer and identifies design characteristics that promote the successful function of materials and mechanisms.

WORM & SPUR GEAR MODELLING .

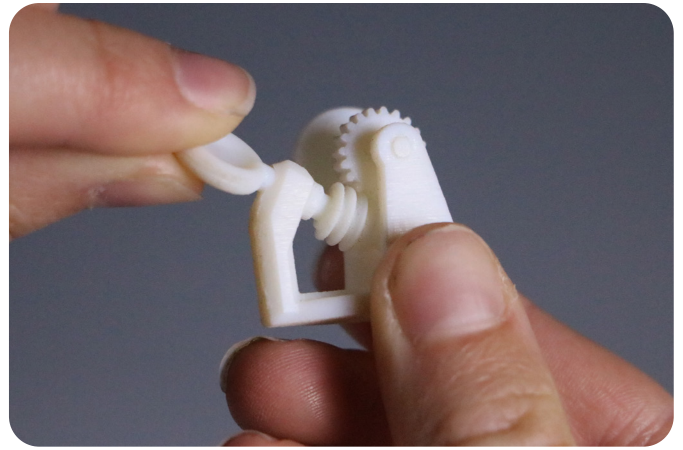


Figure 14: Wor/Spur test operation

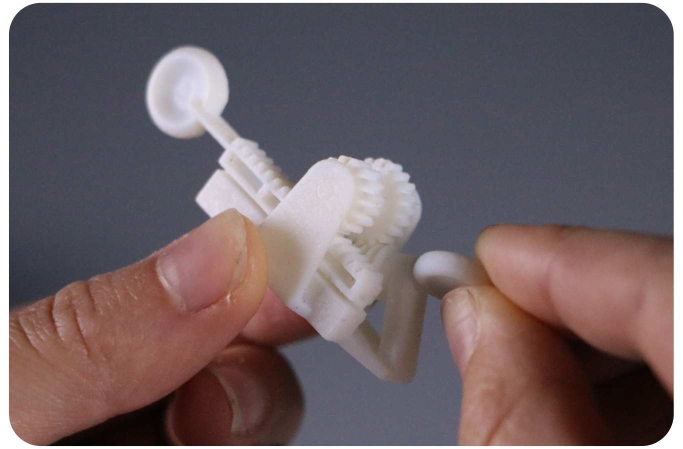


Figure 15: Gear Rack test operation

Instead of hand positioning the puppet's mechanisms, a worm and spur gearset is decided to drive movement, chosen for its ability to convert the large rotation of the worm gear into a much smaller rotation of the spur gear due to a high gear ratio. The worm and spur decrease the positional accuracy required by the animator when posing the character incrementally. Accurate posing in SM is essential as poor positioning can create "chatter" in the final animation, breaking the illusion of continuous smooth movement.

CG worm and spur gears are sourced from Mcmaster-Carr components, available in the Fusion 360 workspace. The gears are imported and positioned into an assembly. Correct positioning is vital as these gears are to be 3D printed in the same file. Too close or overlapping, they will fuse. Too far apart, the teeth of the gears will not function properly.

Once positioned, axles are modelled for each gear to rotate on, a tuning peg to twist the worm and a support structure to hold it all in place. With the axles rotating within the support structure, a tolerence between the two had to be decided on to avoid fusing. This is where the tolerance tool came in handy. Each circle of the tool is modelled as a free-moving part within its housing separated by decreasing tolerances to be filled with support when printed on the J850 as an assembly. After cleaning, the parts are freed from support and rotated, but not all can rotate, with parts beginning to fuse at a tolerance of 0.15mm. Wanting gear rotation to be as secure as possible by minimising lateral movement of the axles, the initial print test is toleranced at 0.18mm, between the smallest functioning tolerance of 0.2mm and the first fusing tolerance.

The print size of the test was chosen based on the ideal size of an SM puppet for the animator posing it. Dimensions were estimated with multiple gears needing to be housed in the head.

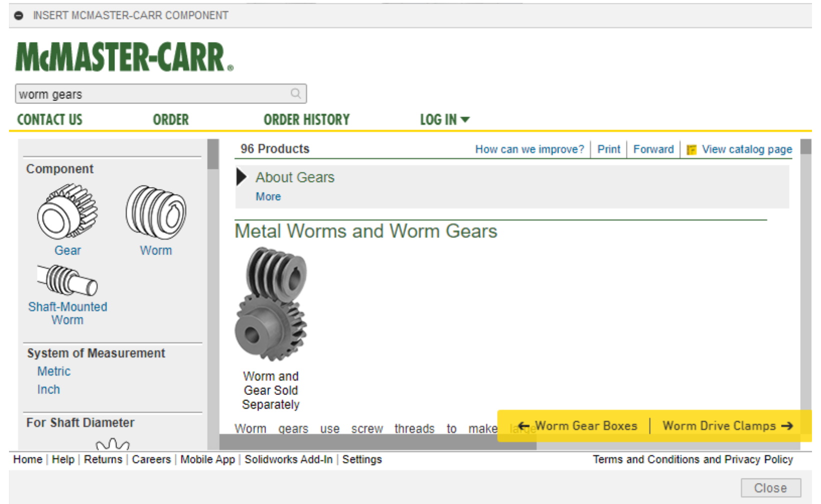


Figure 16: McMaster-Carr Components Fusion 360 Screenshot #1

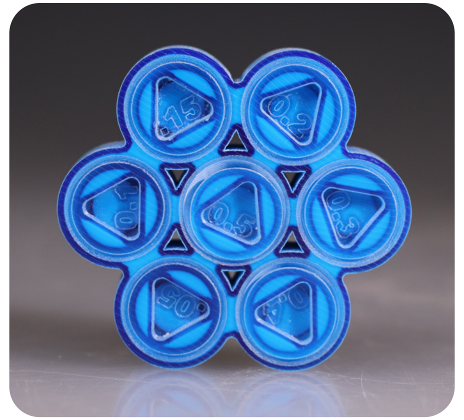


Figure 17: Tolerance Tool #1

Figure 18: Tolerance Tool #2

WORM & SPUR TEST PRINTING .

The test assembly is exported to GrabCad Print, assigned with Vero white and printed. After printing and cleaning, the gears freed up nicely with the help of a bit of force applied to the tuning peg and spur. However, toleranced 0.18mm, there was still enough play between the axles within the supports to be minimised.

So the digital model was tweaked, decreasing the tolerance to 0.17mm.

After testing, the tolerance was further reduced to 0.16mm. Now satisfied with the function of the print and approaching the fusing value of 0.15mm, a distance of 0.16mm is settled on to separate rotating parts from surrounding components.

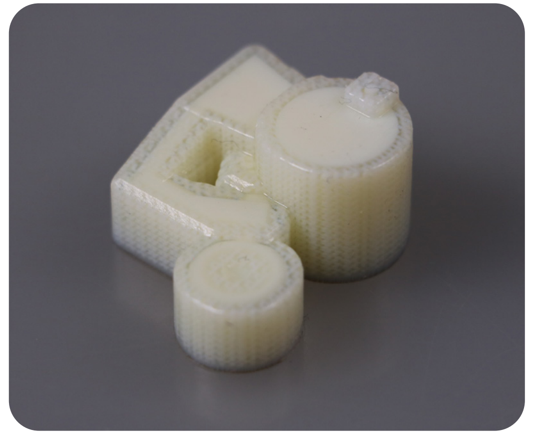


Figure 20: Worm/Spur experiment support

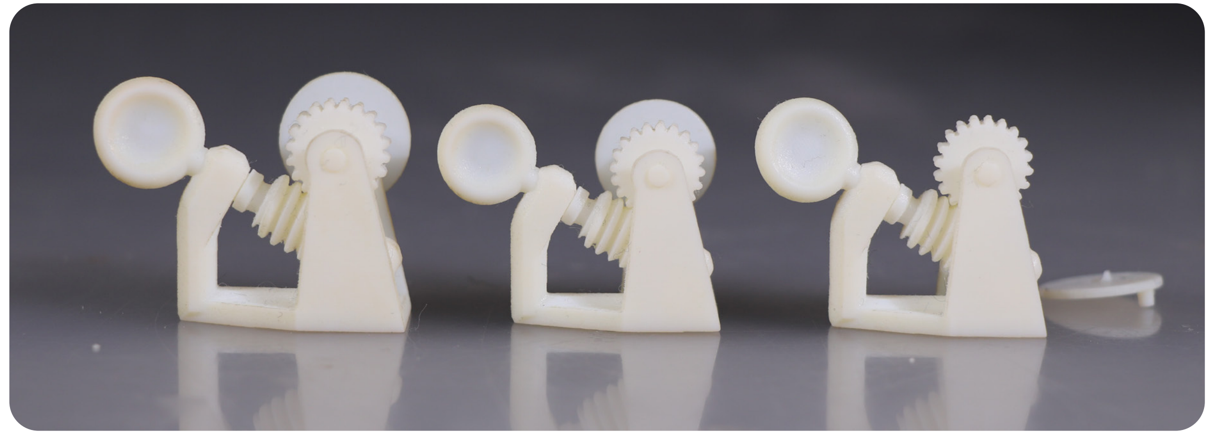


Figure 19: Worm/Spur experiment Collection

Figure 21: Worm/Spur experiment support #2

LATERAL SHIFT GEAR MODELLING .

Now that the driving gear was working, a mechanism that would convert the rotation of the existing spur gear into lateral/planar movement was needed to fulfil the ideated movement of the brows and corners of the mouth.

Once again sourced from Mcmaster-Carr components, an additional spur and gear rack are inserted. The new spur is connected to the same axle as the existing spur, and the gear rack is positioned suitable for printing. A track modelled for the gear rack to slide along.

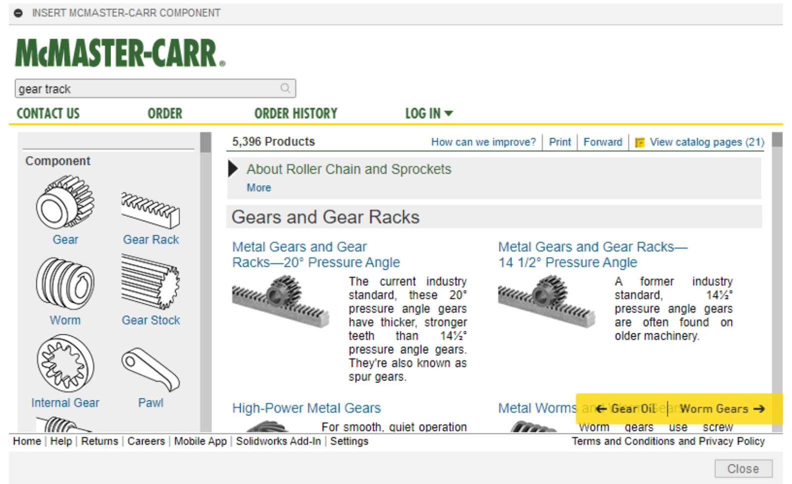


Figure 23: McMaster-Carr Components Fusion 360 Screenshot #2

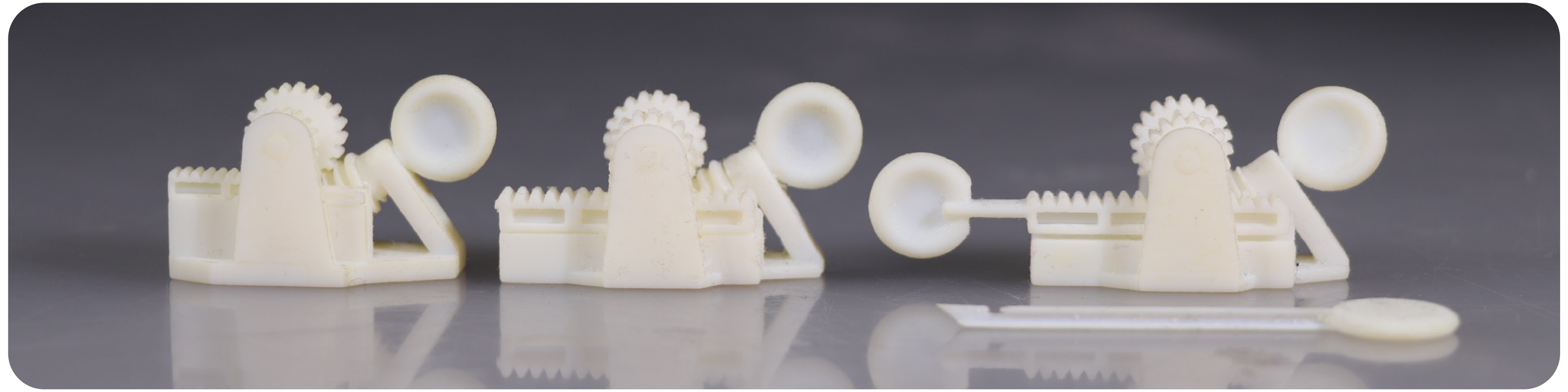


Figure 22: Gear Rack experiment Collection

LATERAL SHIFT TEST PRINTING .

The model is printed with an elliptical profile of the track using the 0.16mm tolerance, tested previously. After cleaning, the gear rack would not budge. So finally, after struggling to free the rack from its track, a pair of pliers was used to crack it open, seeing if the parts had fused. They printed separately, but due to the large surface area of the parts printed so close together, they were seemingly fixed by the thin membrane of support that had nowhere to go.

When remodelling, to decrease the amount of surface area of the enclosed support, holes were created through the sides of the rack, removing the surface area of the sides of these sections. These holes also allow support to be scraped out from each side, releasing enclosed support holding it in place. After cleaning, the track still would not separate. Then, when attempting to apply pressure with a toothpick, the now thinner portions of the gear rack snapped.

For the second remodel, the scale of the gear rack and subsequent spur were increased by x1.4 in an attempt to strengthen the parts allowing more force to be applied. A different square track profile with a slightly larger tolerance along the bottom of the rack was used for this test. After cleaning, there was no more luck with separating the parts.

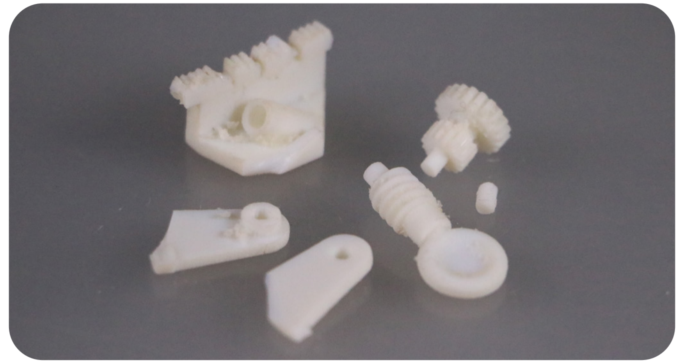


Figure 24: Gear Rack test 1

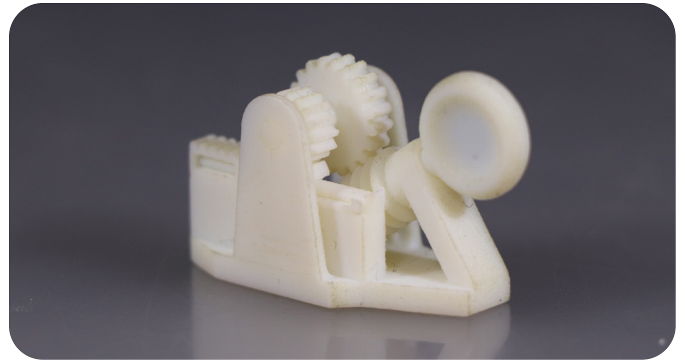


Figure 25: Gear Rack test 2

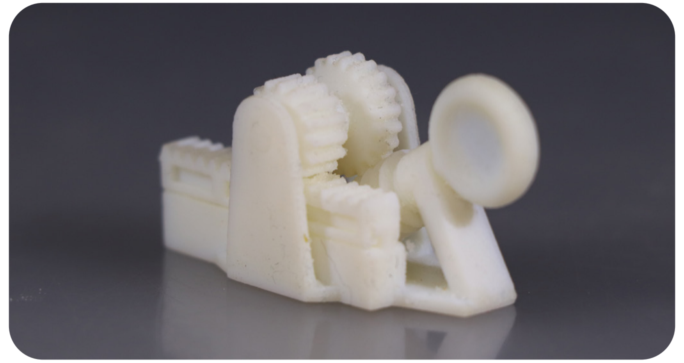


Figure 26: Gear Rack test 3

LATERAL SHIFT TEST PRINTING .

For the third remodel, the profile of the gear rack was again changed, this time to a triangle offering less surface area along its length. It was modelled so that tools printed alongside the mechanism can be inserted, clearing portions of support along the base of the rack and sides of the stem. In addition, a break-away grip tab is added to aid in pushing and pulling along the track's path. After clearing support with the tools and pushing, pulling and twisting the grip tab, freeing the moving parts, the mechanism worked as intended.

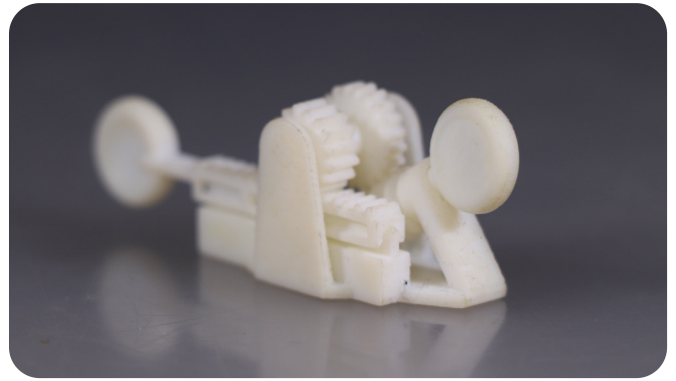


Figure 31: Gear Rack test 4

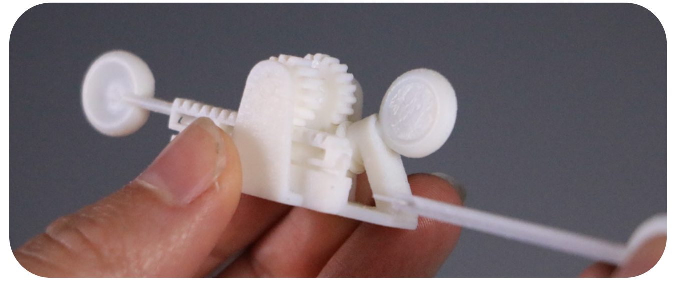


Figure 30: Gear Rack test 4 tools operation

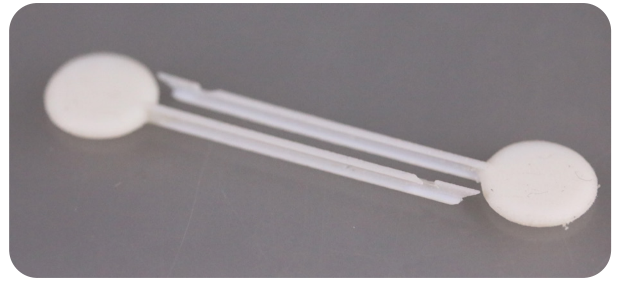


Figure 27: Gear Rack test 4 tools

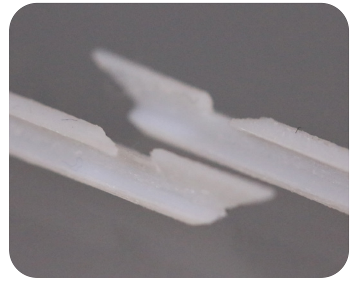


Figure 28: Gear Rack test 4 tools #2

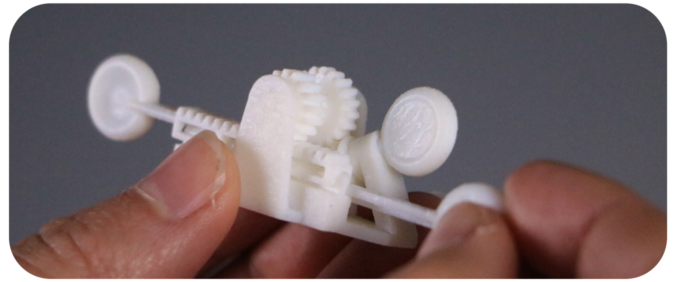


Figure 29: Gear Rack test 4 tools operation #2

VISUALISATION .

3D models are placed in a modelled draft assembly throughout the gearset print testing process, including possible mechanisms. This allows me to visualise how gears may be placed and drive ideated movement. This visualisation offers insight into possible orientation issues of parts placed in relation to other components during operation.

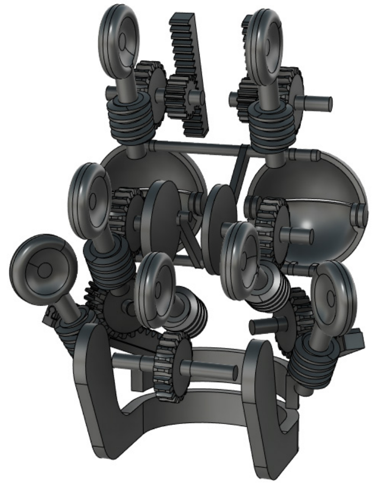


Figure 32: Fusion 360 draft #1

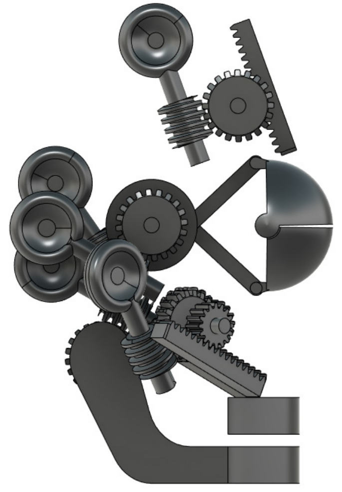


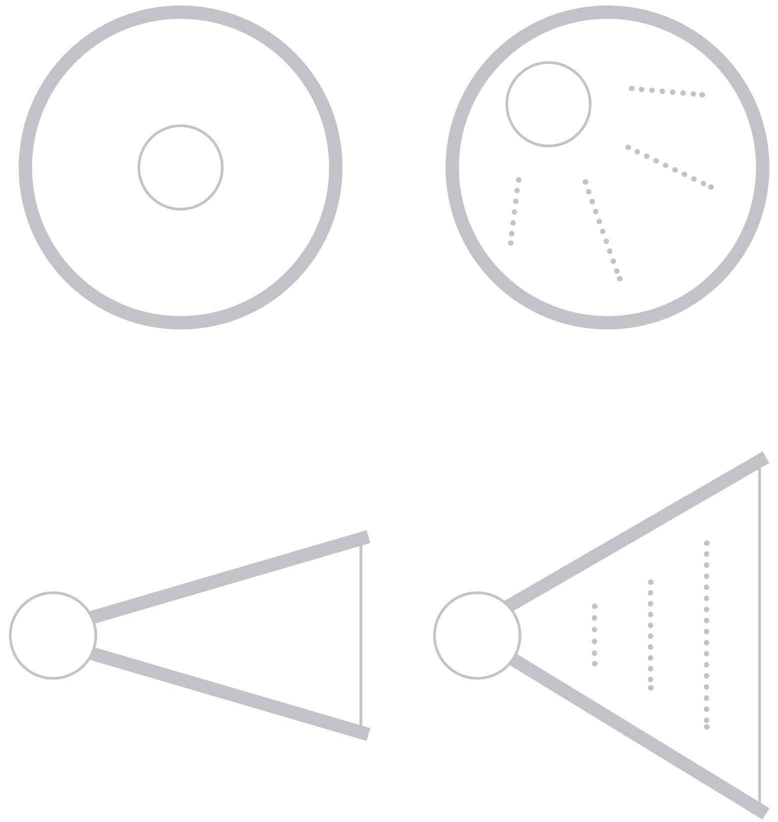
Figure 33: Fusion 360 draft #2

Figure 34: Fusion 360 draft #3

SKIN TEST PARAMETERS .

When material testing the flexible Agilus, two types of stretch needed to be assessed, as seen in sketches planning possible movement.

Figure 35: Stretch Test Parameters



Enclosed stretch

stretch of Agilus when fixed points surround the deforming section, seen in the planar movement of the brows and smile of the draft fusion model Jerrald driven by the gear rack mechanisms.

Open-ended stretch

stretch of Agilus when two fixed sides move away from each other with an open, un-fixed side, seen in the jaws pivoting movement away from the skull, the open end being the parting of the lips.

MATERIAL MIX DESITY TESTING .

The Agilus material on campus is translucent. With a desire to add colour, a test swatch was poked, prodded, and stretched. The swatch shows a range of mix ratios between 100% clear, soft Agilus, and 100% rigid cyan Vero. A shore hardness value characterises each ratio's density. However, after deform testing, it was made clear that incorporating the Vero greatly reduced the deform and stretch ability of the Agilus, especially at a high enough ratio to change the colour effectively. So for this research, 100% Agilus will be used for the skin.

Also observed is the material's ability to stretch further in areas of lesser wall thickness with the same force applied. After observing the weak hold strength of the tested Vero gears, this increase in the skin's ability to stretch can reduce the force required to deform and hold position change along with stress exerted on the gears holding it, decreasing likely hood of gear malfunction or breakage.

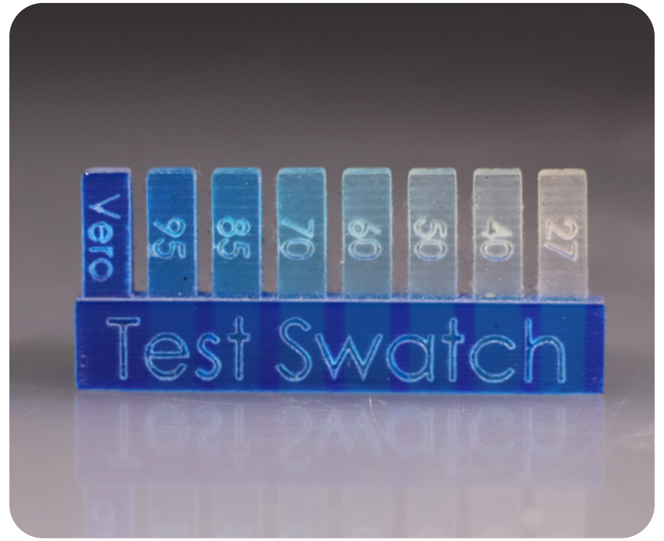


Figure 36: MMP variable density test #1

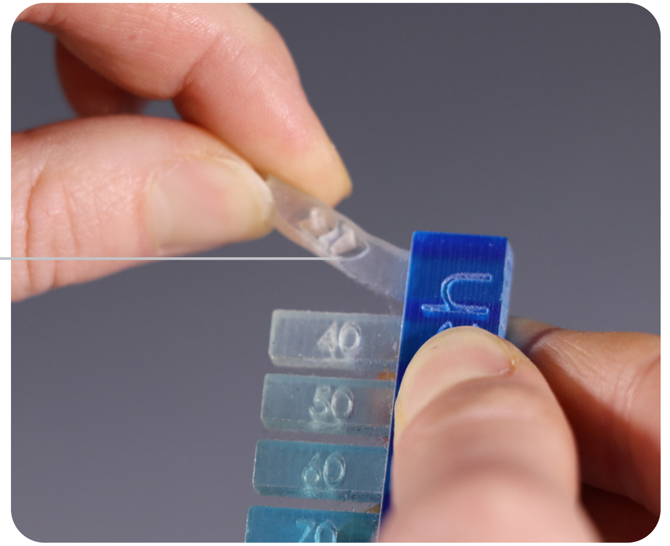


Figure 37: MMP variable density test #2

SKIN TEST COMPONENT MODELLING .

With the test parameters finalised. It was time to test the stretch capability of the Agilus material in the context of a deforming face. First, a face is needed. A CG stylised character bust was sourced from Turbo Squid, an online marketplace for buying and selling digital 3D models. It offered a range of files to use, one of which was a Blender file, the modelling software I would use from this point on. Importing the file into the blender workspace offered a low poly mesh of the bust. The head 3D mesh was used to model the test's skull, jaw and skin components. Other meshes are used in the modelling of the full-head final application.

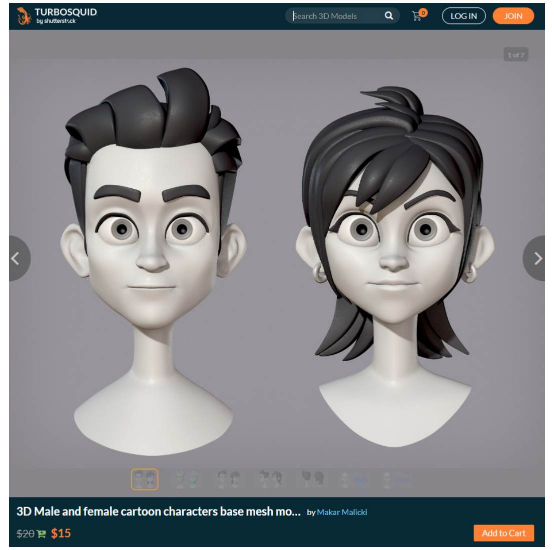


Figure 96: Turbo Squid CG character

Figure 38: Turbo Squid Blender Screenshot #1

Figure 39: Turbo Squid Blender Screenshot #2

Figure 40: Turbo Squid Blender Screenshot #3

DIGITAL MODELS .

The skin mask of the test is given a depth of 1mm, the thinnest recommended wall thickness for an Agilus part the the campus's Poly-jet technicion, in an attempt to maximise stretch.

Beneath the skin is a front skull plate with a section of the brow missing. In the centre is a pressure paddle embedded in the skin to be moved and stretched by hand, simulating the movement of the gear rack and testing the enclosed stretch, characterised by the lowering and raising of the brow.

Also beneath the skin is a hinged jaw, toleranced at 0.16mm, which opens and closes the mouth, testing the open-ended stretch of the cheeks when the mouth is opened.

Figure 41: Skin Test, Agilus

Figure 42: Skin Test Assembly #1

Figure 43: Skin Test, Vero

Figure 44: Skin Test Assembly #2

SKIN TEST PRINTING .

The assembly is exported GrabCad Print. Pure Agilus is assigned to the mask and black Vero to the jaw, skull and pressure paddle, adding contrast to aid in identifying any print issues when bonding with its flexible counterpart.

The priority function of GrabCad Print is used to ensure the separate parts are fixed to one another when printed. With the different parts of the assembly modelled to overlap, different priorities are assigned to dictate which part prints in that overlap. With no distance between the two parts, they fuse at the outer surface of the higher priority part. Priority 1 is given to the pressure paddle as it needs to be embedded and anchored in the skin. Priority 2 was given to the skin to keep the thickness uniform across the whole face to keep stretch consistent. Priorities 3 & 4 are given to the skull and jaw to accommodate the uniform thickness of the skin and ensure a bond.

After printing and cleaning, the test was revealed, with the jaw hinging nicely and all parts bonded where they should be. White discolouration can be seen on Vero surfaces that are bonded to the skin. This may be due to the priority overlap of the two complex meshes causing the resulting imperfections, but this is no reason for concern. In practice, the skin will ideally be printed in an opaque Agilus to hide the puppet's inner workings.

Figure 45: Skin Test experiment print #1

Figure 46: Skin Test experiment print #2

Figure 47: Skin Test experiment print #3

ARTICULATION TESTING .

Figures 48 and 49 show the jaw articulation as a result of the open-ended stretch. The mouth's opening offers a look of surprise, especially when coupled with the raised brow, and although the closing/gritting of the jaw is over-extended, it results in top lip protrusion looking a bit like a frown. However, in reality, it looks more like someone missing their teeth pulling a funny face.

Conclusion

Far less force was needed to deform the face through jaw movement, the open end offering less resistance. Although, a remodel will be required as the sharp corners of the mouth resulted in tearing that only worsened over time.

Figure 48: Mouth pose #1

Figure 49: Mouth pose #2

Figures 50 and 51 show the articulation of the brow as a result of the enclosed stretch. Effective in deforming upward to offer a surprised expression and downward to offer a resemblance of anger.

Conclusion

Although effective in its movement when stretched by hand, the force required to stretch and hold the deformation feels too much for the gear rack mechanism to handle. Likely resulting in breakage or not being strong enough to deform at all. For this reason, neither enclosed stretch nor gear rack mechanisms will be used.

Figure 50: Brow pose #1

Figure 51: Brow pose #2

MEET THE MECHANISMS .

Eyes

The eyes are restricted to vertical movement as it works best with the tested mechanism. A spur between the eyes rotates around an axle mounted at each side of the skull. The spur, axle and eyes are connected as one body.

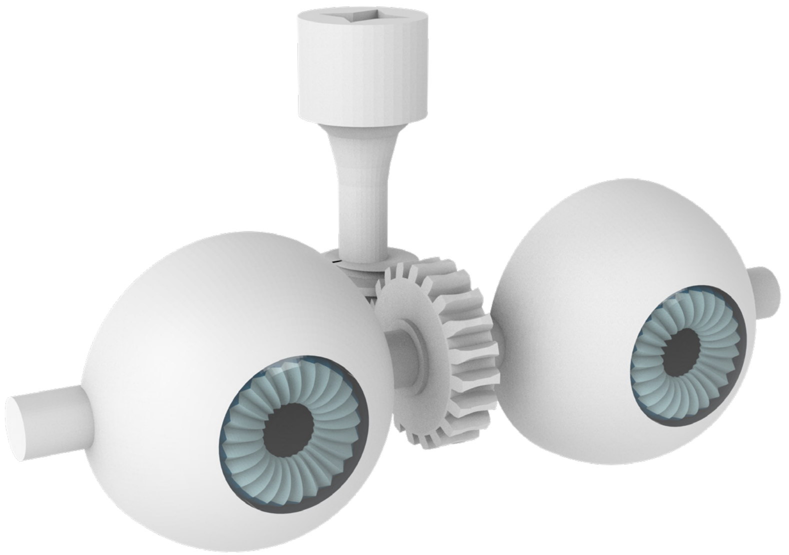


Figure 52: Vertical Eye Movement Mechanism

Jaw

The jaw's spur is located in the centre of an axle running through its pivot point. The axle is thickened, and the worm and spur are scaled up to add strength in order to handle the rebound force of the stretching Agilus when posed open.

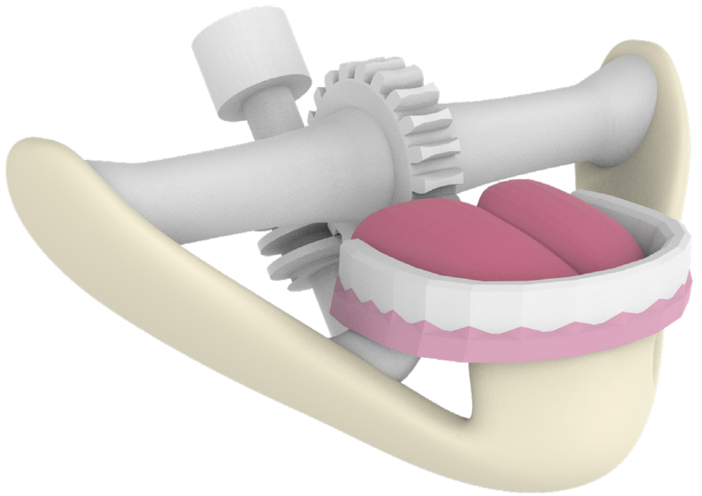


Figure 53: Jaw Hinge Movement Mechanism

MEET THE MECHANISMS .

Eyebrows

The mechanism for positioning the eyebrows has been redesigned to avoid the use of enclosed stretch and gear racks. It is now positioned by directly using the rotation of the tested worm and spur, each rotating independently around its outermost point, raising and lowering the innermost point. This redesign takes inspiration from mechanisms used in live puppetry.

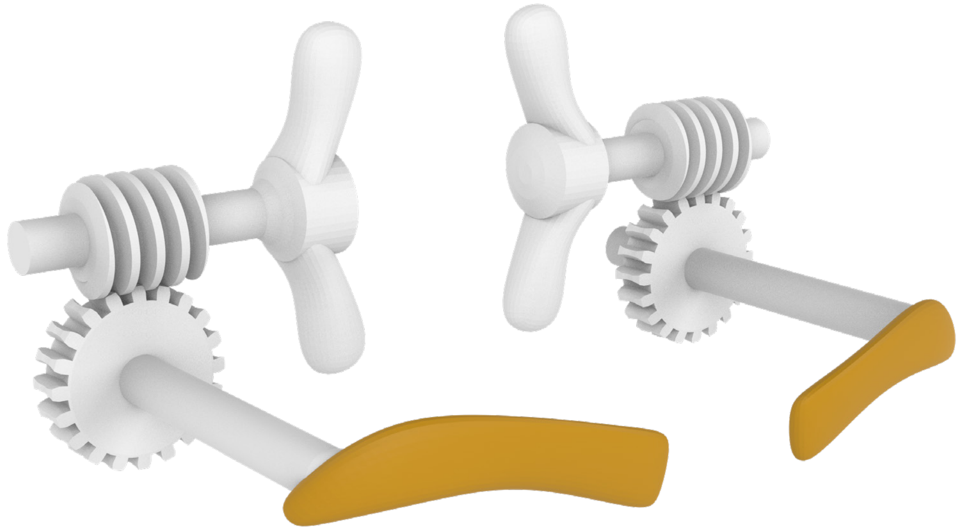


Figure 54: Brow Movement Mechanism

Eyelids

The top and bottom eyelids are rotated independently with the spur of each positioning gear, driving a wheel to shift crossbars attaching the left and right sides, opening and closing both sides simultaneously. Through attachments, the eyelids pivot around the existing axle of the eye movement spur. This design takes inspiration from blink mechanisms used in live puppetry.

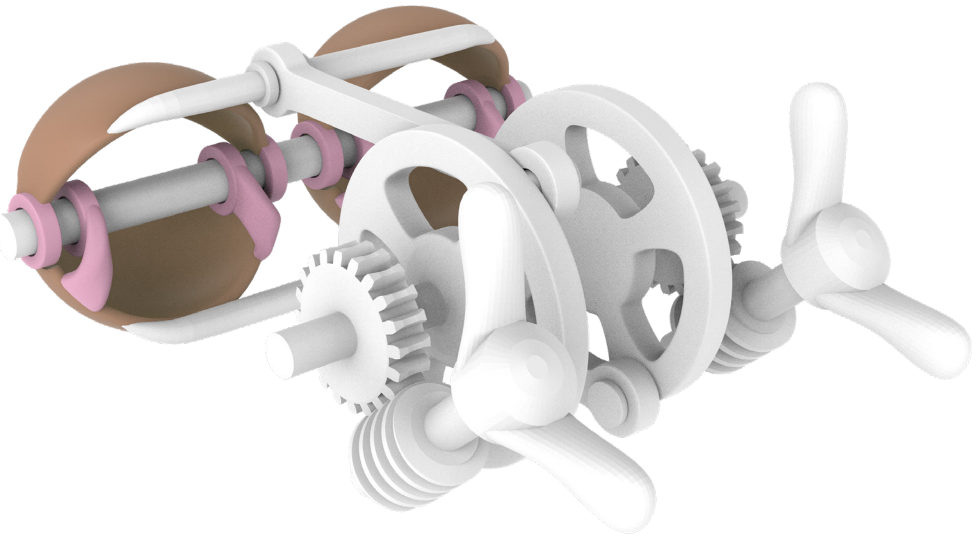


Figure 55: Eyelid Movement Mechanism

PLACEMENT WORKFLOW .

With numerous moving parts in this model, tolerance and secure gear placement are very important. However, modelling and checking these factors one by one felt too time-consuming, so to streamline this process while ensuring these are accounted for, a master gearset is created. This gearset features spacing tools (green), placed 0.16mm from each side of the gears, and a tolerance tool (red), surrounding the axle scaled so all surfaces of the axle are 0.16mm away from the surface of the tool. This master gearset and its tools are copied, positioned, and parts scaled where needed.

When in place, axles are extended to where support structures can secure them, along with the tolerance tool of each axle.

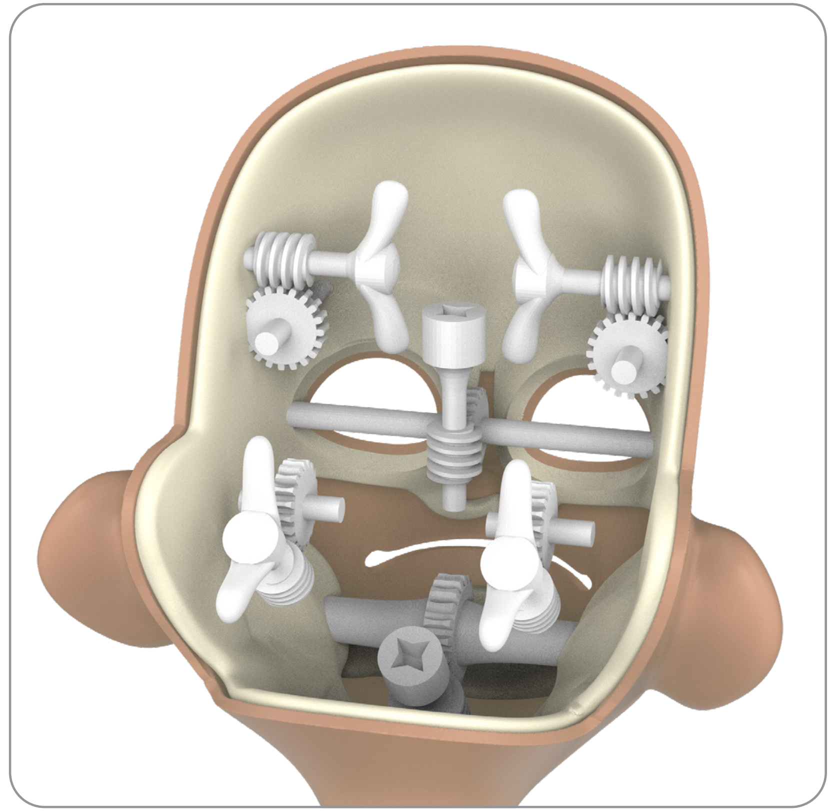


Figure 56: Gear Placment

Mechanisms are placed in relation to their corresponding gearset drivers.

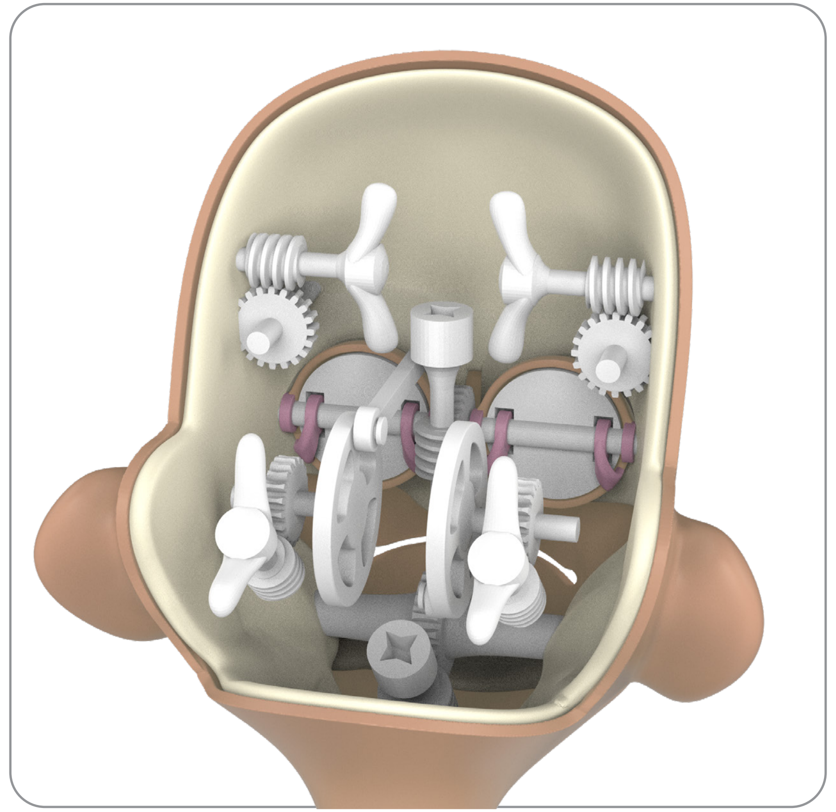


Figure 57: Mechanism Placment

PLACEMENT WORKFLOW .

Support structures are modelled, intersecting with both sides of all axles.

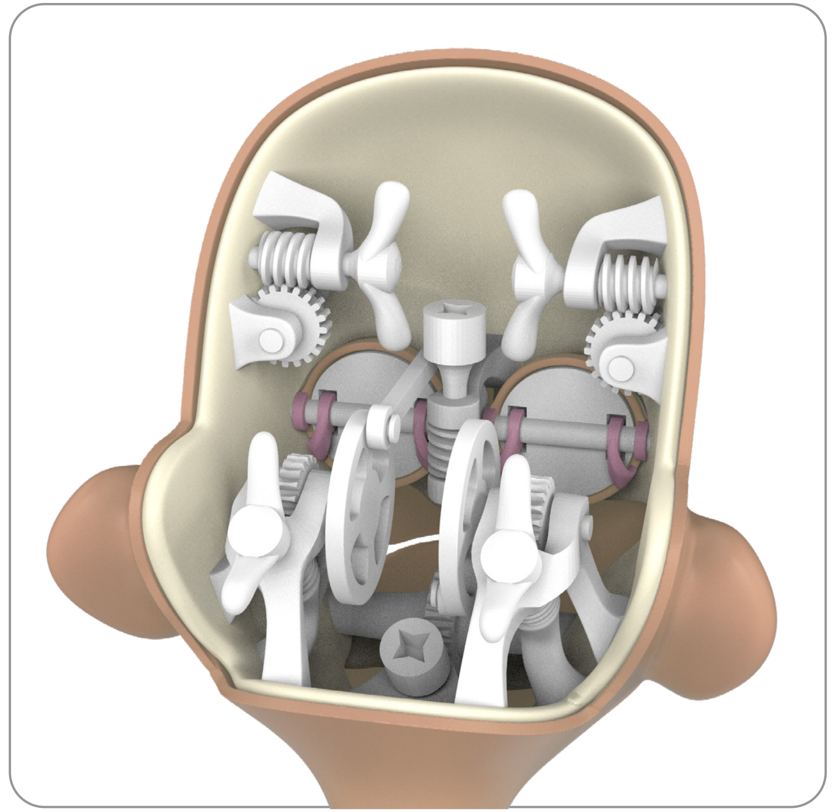


Figure 58: Support Placment

Once everything is in place, the spacing tools are connected to the support structures they lie in, and the tolerance tools are used to remove sections of all parts that pass through them. What is left are accurate tolerances and gears spaced securely.

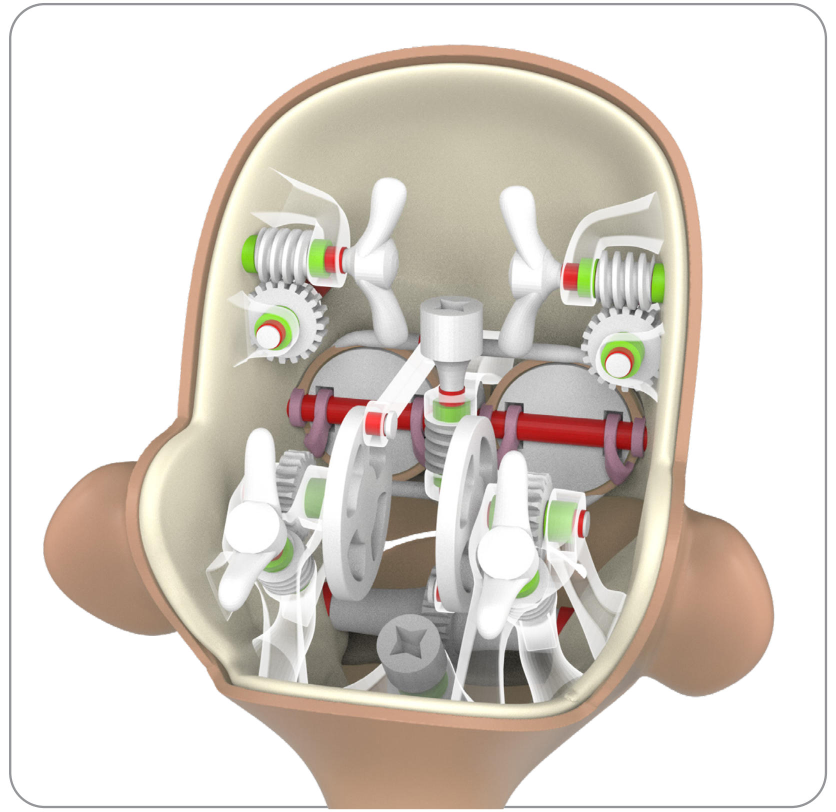


Figure 59: Placment, Tool Apply

EYE MECHANISM TEST PRINTING .

To test the effectiveness of the pre-assembled print mechanisms, movements related to the eye are isolated and supported for printing. Due to these being the most complex of the head, with the eyelids being the only non-direct driven movement and include parts rotating independently within each other, along with thin componentry, they are at greater risk of breakage or malfunction.

After assigning a wider range of colours to simulate the hues of the skin, skull and eyes, trying to keep within the style of the character, the assembly was printed, carefully cleaned, and moving parts freed.

Issues

While freeing, the eye movement worm axle snapped in its bottom support. In addition, the grinding of the bottom eyelid's worm caused skipping of its spur.

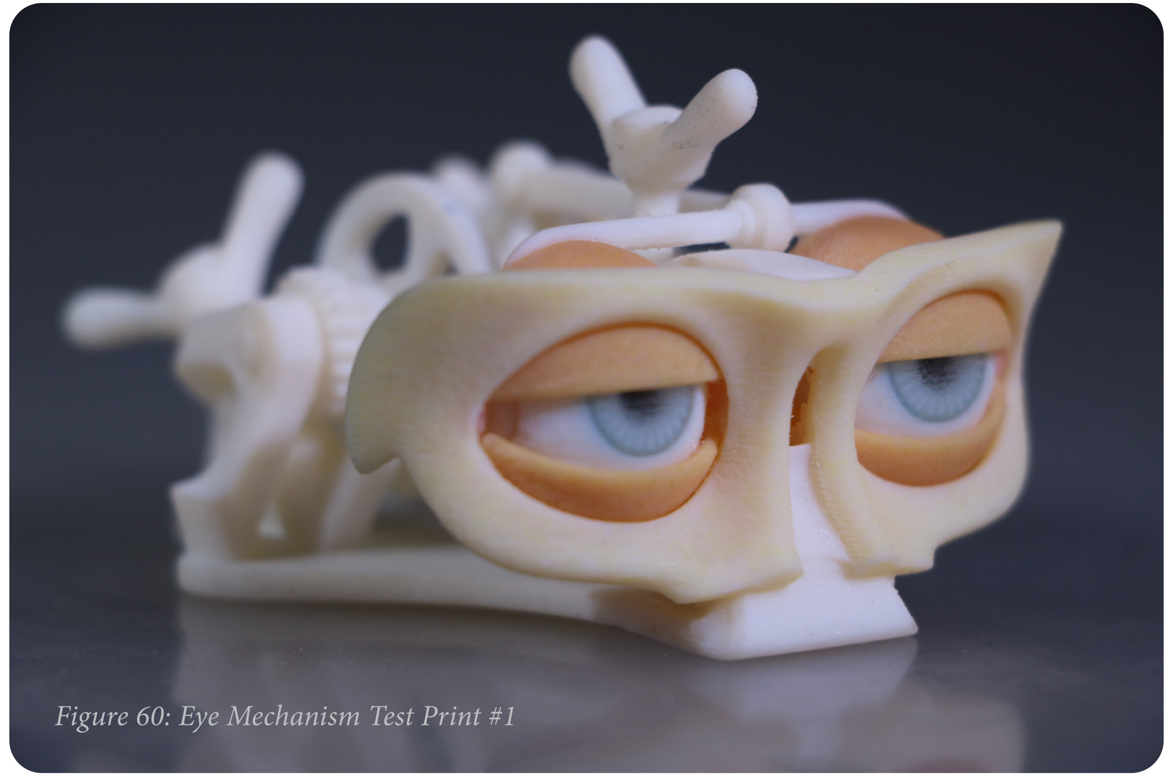


Figure 60: Eye Mechanism Test Print #1

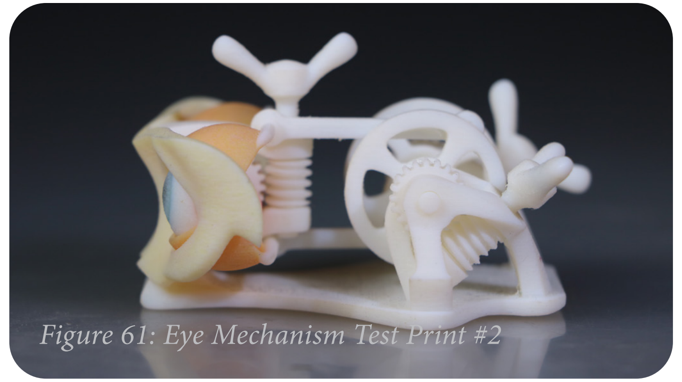


Figure 61: Eye Mechanism Test Print #2

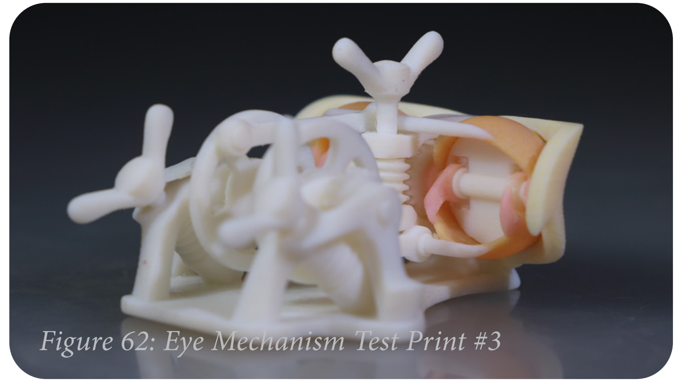


Figure 62: Eye Mechanism Test Print #3

POSE TESTING .

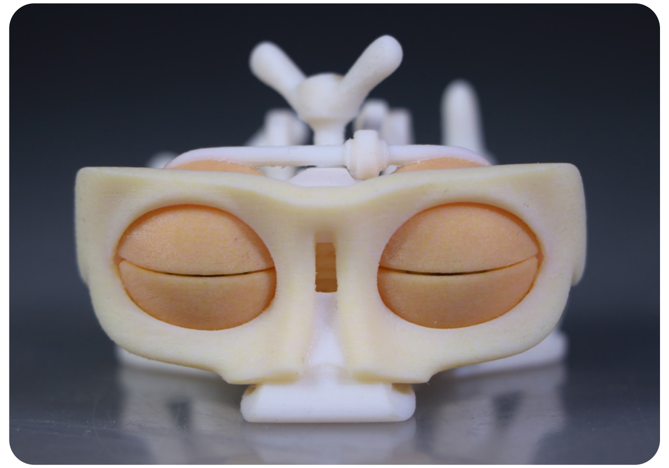


Figure 63: Eye Mechanism Test Pose #1

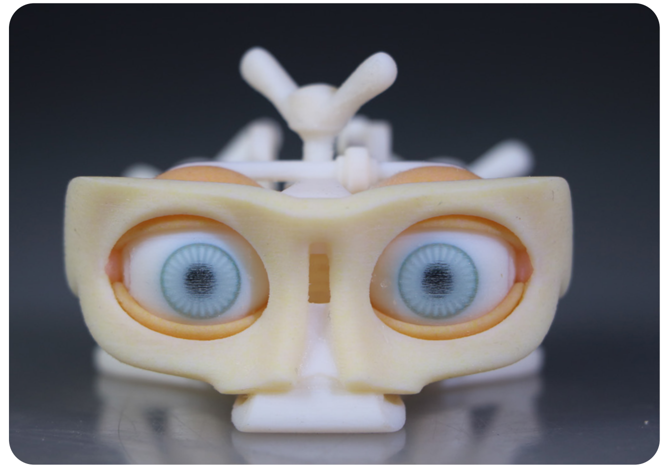


Figure 64: Eye Mechanism Test Pose #2

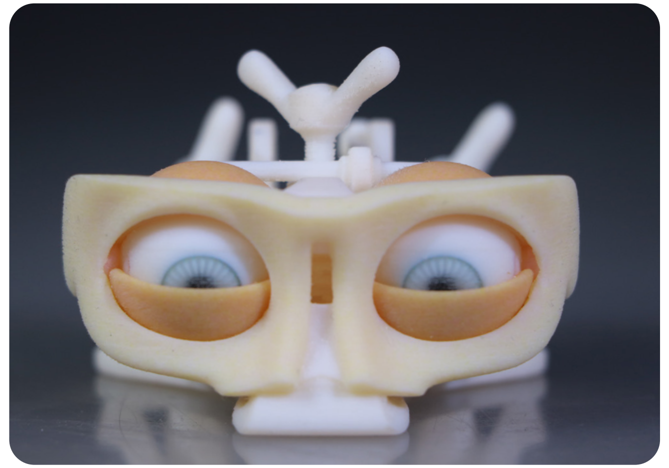


Figure 65: Eye Mechanism Test Pose #3

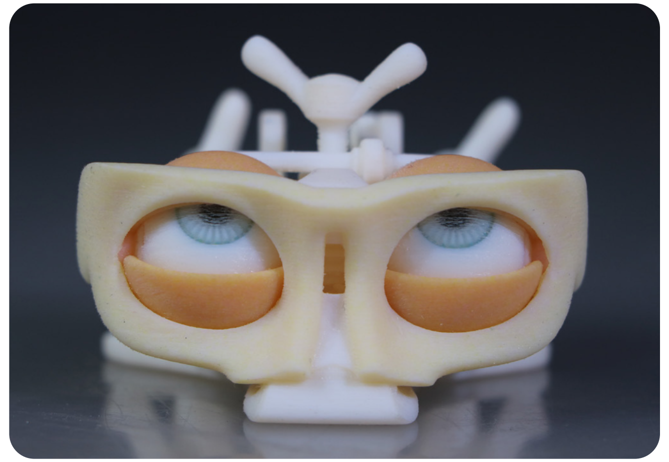


Figure 66: Eye Mechanism Test Pose #4

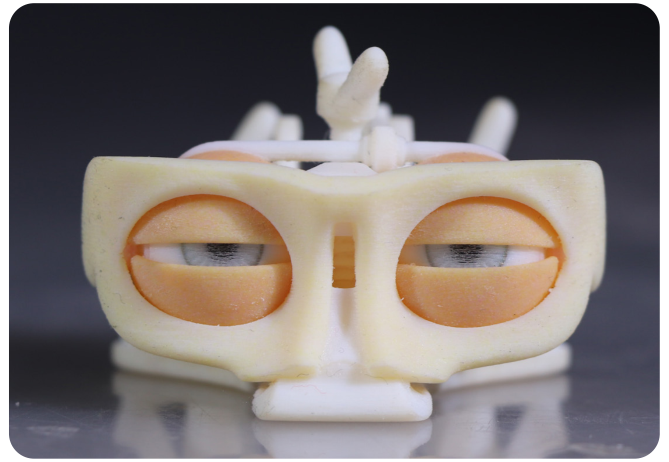


Figure 67: Eye Mechanism Test Pose #5

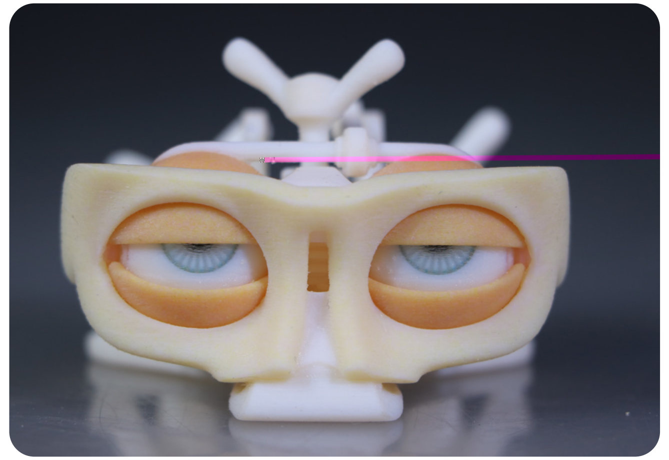


Figure 68: Eye Mechanism Test Pose #6

GEARSET REMODEL .

Strengthened Axle

With the thickness of the axles placed in the eye mechanism test modelled at 3mm, it was too much for the worm gear of the eye movement to handle, resulting in the snapping of the bottom axle. In an attempt to fix this, the axle thickness was scaled to 4mm.

Spur Modify

Its digital file was remodelled to avoid skipping the spur gear seen in the bottom eyelid gearset. The teeth of the spur extended, and a slight angle was added, allowing them to fit further into the angled spiral of the worm. This remodel is an attempt to minimise the impact frictional wear has on the function of the gearset.

These alterations were test printed using the same supports of the eye mechanism test. However, more force had to be applied to free this worm gear, which shattered along its axle and bottom support.

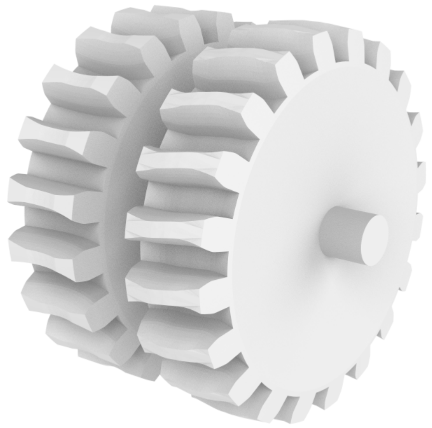


Figure 69: Modified Spur Comparison

Figure 70: Gearset Remodel Print #1

GEARSET REMODEL .

Beveled Tolerance Tool

Theorising that this greater resistance to being freed is caused by a greater surface area of enclosed support due to the increased circumference offered by the new axle, the axle supports were remodelled to decrease this. The tolerance cutting tool was altered to create a bevel starting near the inner edge of the axle supports, expanding out and removing more material. This gives the support material room to shift and crumble, also offering access to be partially removed with a toothpick. After cleaning the parts are freed with no issue, leaving the spur teeth positioned further into the worm spiral.

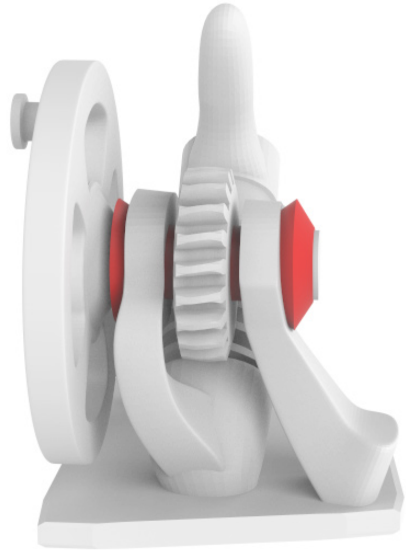


Figure 71: Beveled Tolerance

Figure 72: Gearset Remodel Print #2

Figure 73: Jeffrey Blender Screenshot #4

4

JEFFREY.

Jeffery is the name given to the final design output of the research. This chapter is where lessons learned in the experimentation phase are applied to his design process. Jeffrey's birth attempts to fulfil the output goal previously stated.

ALTERATIONS .

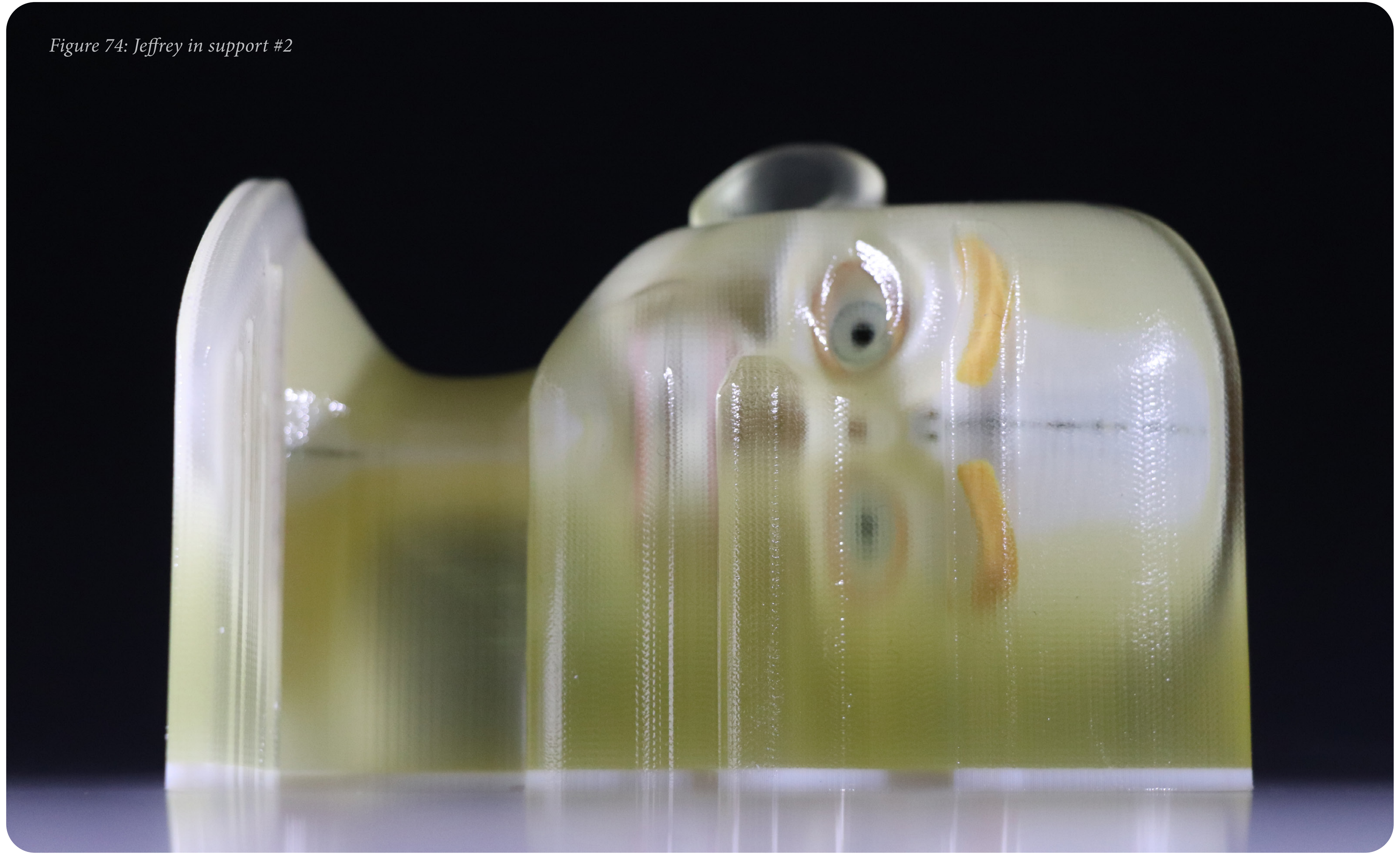
Mouth
The corners of the mouth are rounded to give the material less opportunity to tear.

Axles
The master gear is altered, thickening all axles to 4mm for added strength.

Tolerance Bevel
Once master gears are placed, all tolerance tools are bevelled.

Pressure Tabs
Pressure tabs are added to the end of the eyebrow spur axles and the rear of the eyeballs to offer leverage when freeing from support.

Figure 74: Jeffrey in support #2



PRINTING .

Alterations are made, and tolerance/ spacing tools are applied. The assembly is then exported to Grabcad print, where colour and materials are assigned to their correct, and part priority is carefully chosen. The print orientation places the assembly on its side, building the puppet in layers from ear to ear. Print layers now running perpendicular to the parting of the mouth, hopefully offering more resistance

Cleaning was complete in the order of, removing large areas of support by hand, clearing support surrounding the outside of the model while keeping that surrounding the eyebrows that could use some beefing up using the skewer and toothbrush, carefully breaking up the inner section first from the back then through the mouth, rinsing and soaking in warm water with warm water throughout.

Figure 76: Jeffrey in support #3

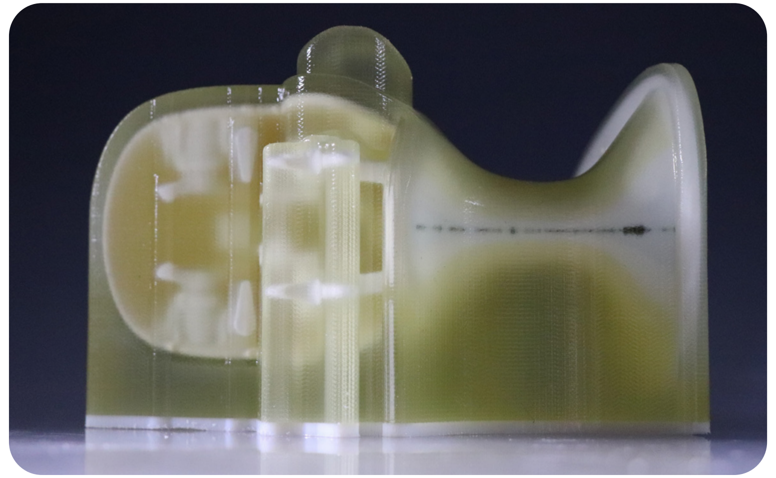


Figure 75: Cleaning Jeffrey

POSE TESTING .

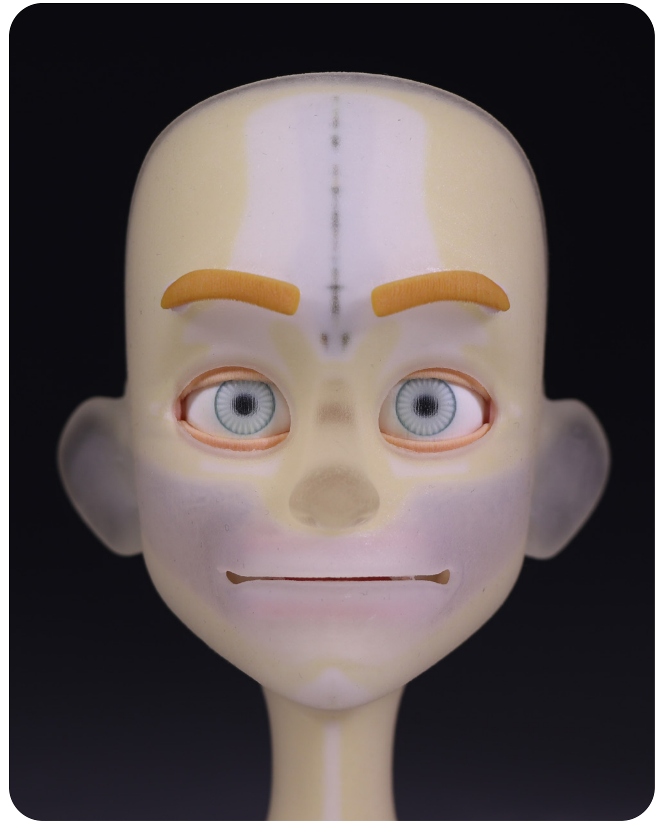


Figure 76: Jeffrey Test Pose #1

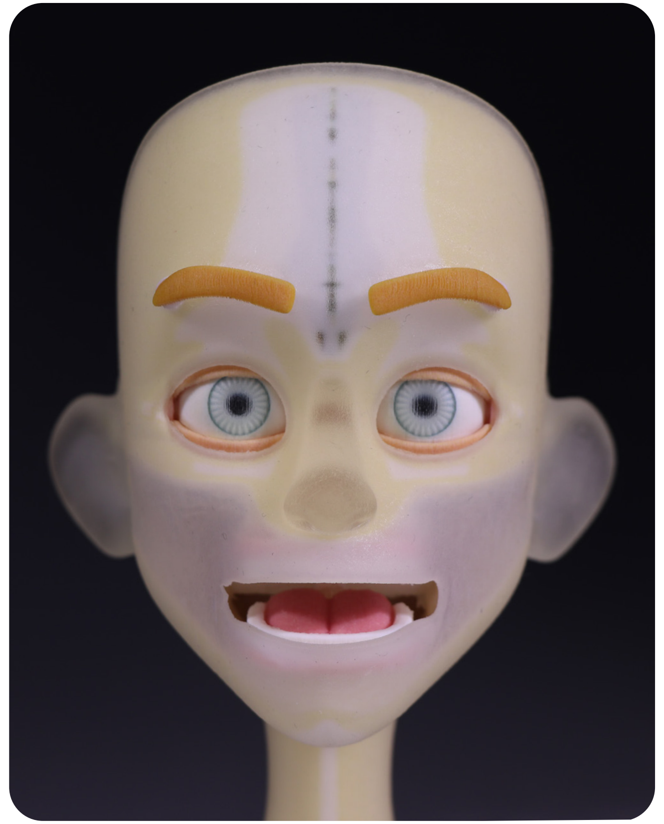


Figure 77: Jeffrey Test Pose #2

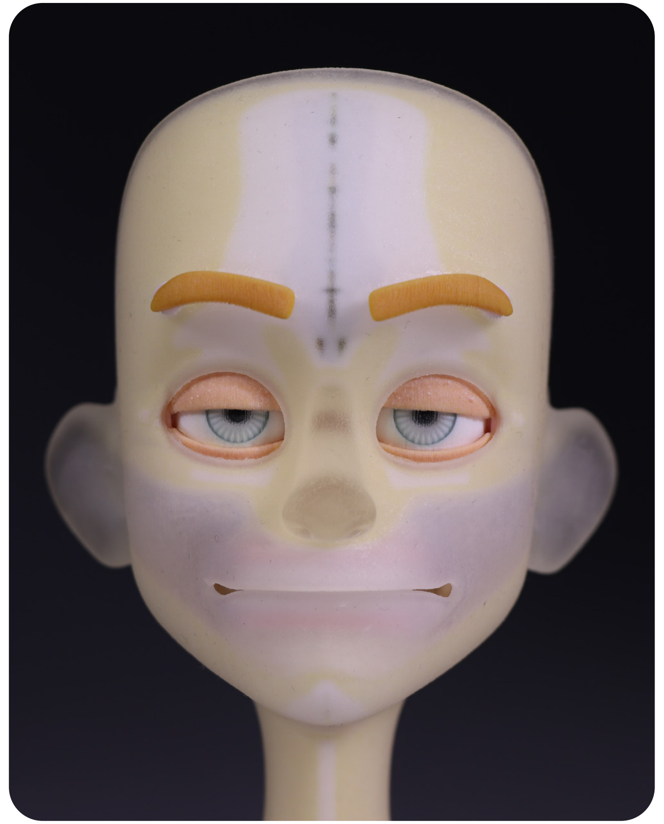


Figure 78: Jeffrey Test Pose #3

POSE TESTING .

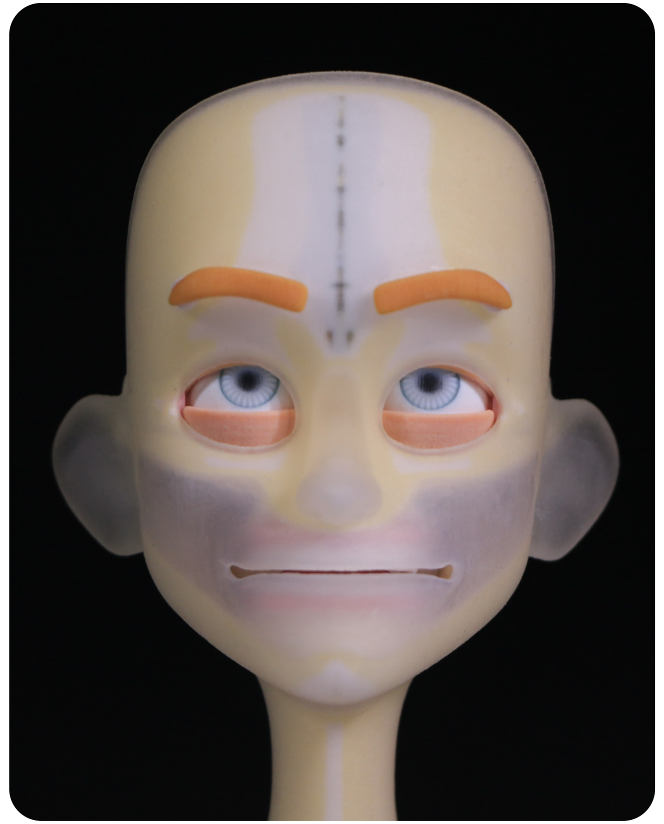


Figure 79: Jeffrey Test Pose #4

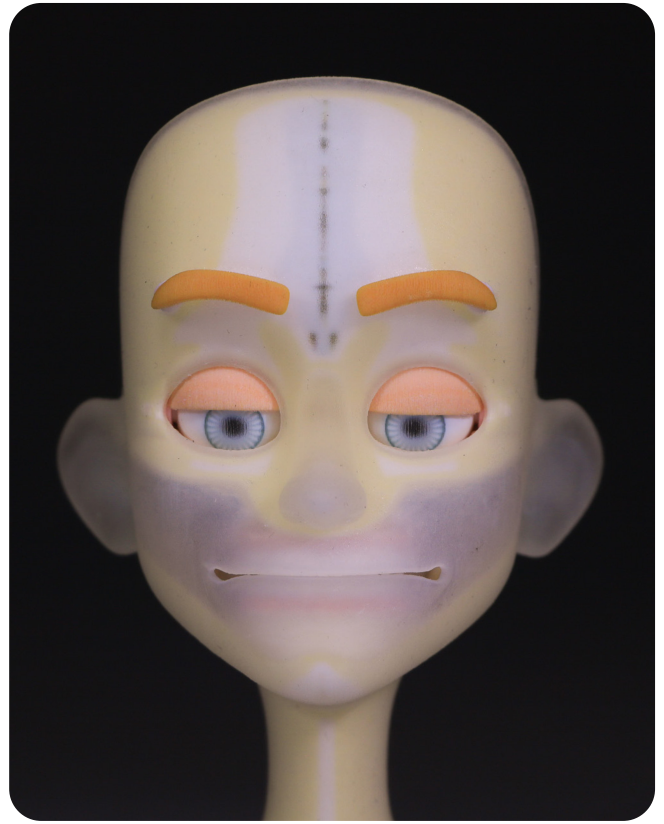


Figure 80: Jeffrey Test Pose #5

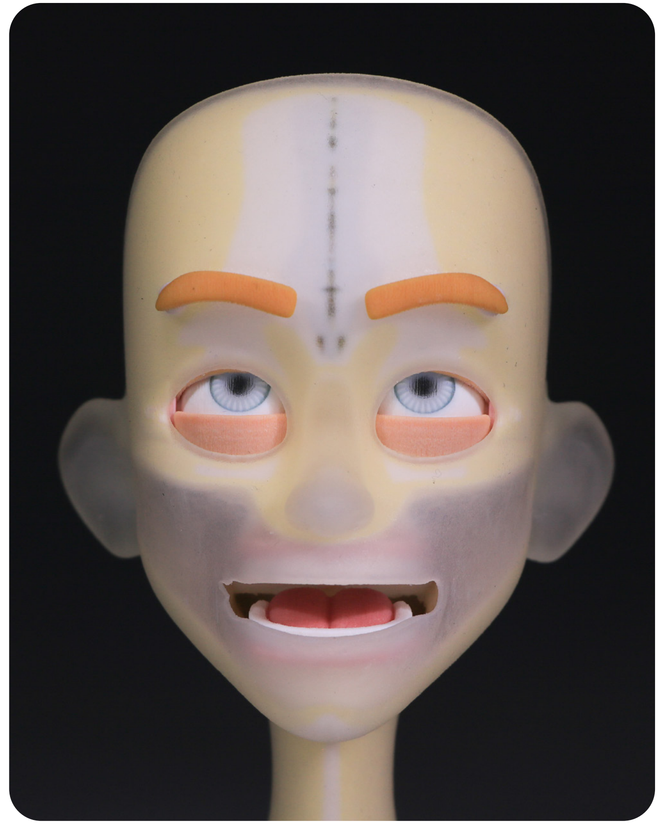


Figure 81: Jeffrey Test Pose #6

ISSUES .

Modelling

Although the assembly was thoroughly checked, one tolerance was missed—the spur of the eyebrow mechanisms from the skull, resulting in fusing and stopping the eyebrows from being posed. This is quickly fixable due to the digital design methods of this process.

Print orientation

While attempting to free all of the moving parts, it was made clear that the parts that rotated around the vertical axis when printed were far more difficult to move. These included the eyelids, eyes, jaw and the eyelid mechanisms connecting rod that attaches driving wheels to crossbars. More force was applied after additional cleaning and soaking, this freed the spurs, but the movement of the connecting rod flexed and snapped the crossbar of the top eyelid, leaving them to rotate independently. While applying to push on the pressure tabs, the eyes were freed but took the bottom eyelids with it, snapping their crossbar, leaving them to rotate with the eyes. The jaw was able to be freed successfully due to its strength and leverage that could be applied to the chin.

Upon inspection of one of the crossbar pieces, tiny hairs can be seen around one-half of its circumference in the direction layers are printed. This phasing of material on both sides of the tolerances locks the parts, making them harder to free from the now even more enclosed support material, far more than when printed on other orientations. This is more than likely the cause of the freeing issue seen in the eye mechanism test and the subsequent axle snap.

Tearing

Minimal tearing is still seen in the corner of the mouth, fixable through further experimentation.

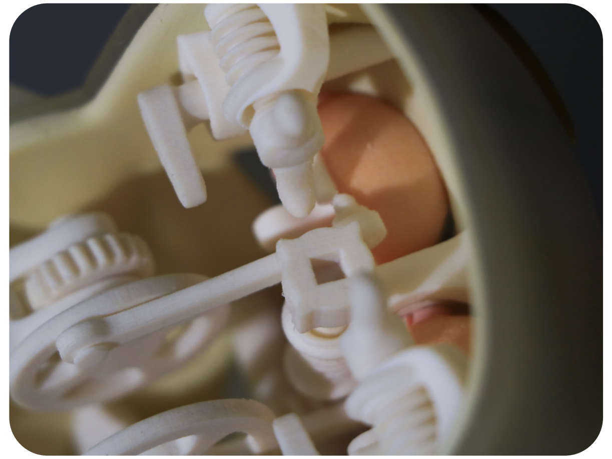


Figure 83: Print breakage #1

Figure 84: Print breakage #2

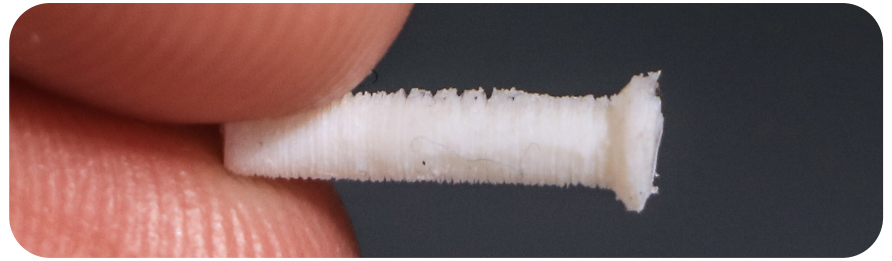


Figure 82: Print-line hairs

Figure 85: Modelling issue

ISSUES .

The breakage of the top eyelid crossbar allowed an additional, possibly intoxicated pose.

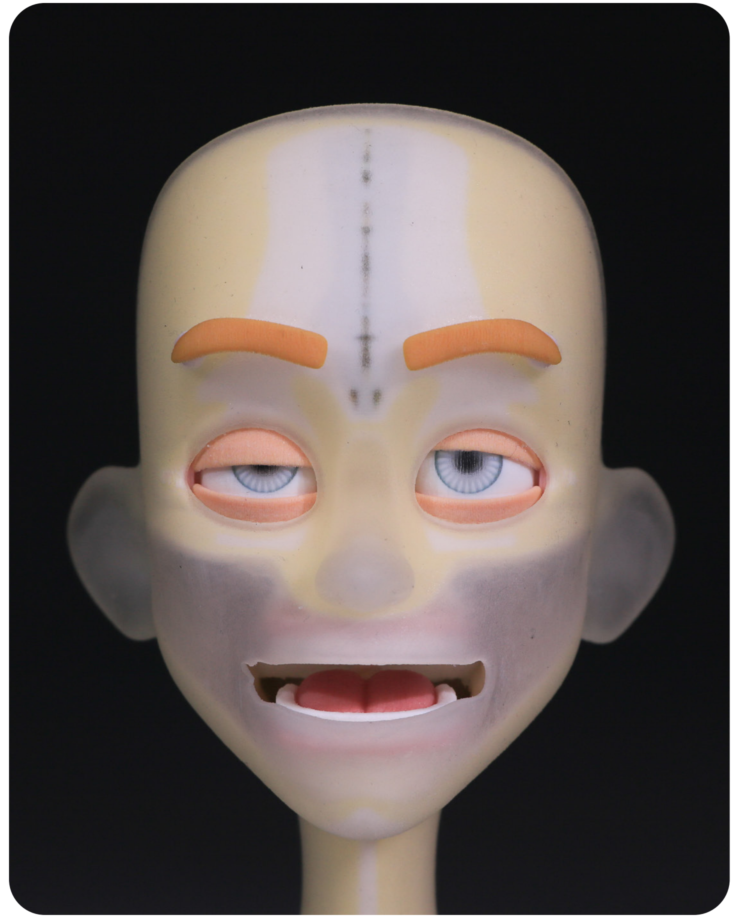


Figure 86: Jeffrey Test Pose #7

OPERATION .

Figure 87: Jeffrey Skrewdriver Operation

Figure 88: Jeffrey Hand Operation

PHYSICAL INTERACTION .

The puppet's thin, flexible skin allows it to be easily physically deformed and manipulated. This opens up the opportunity for interaction with other props of the set when being posed, offering greater options of expression and relationship with the character's environment.

Figure 92: Jeffrey Lip Deform #1

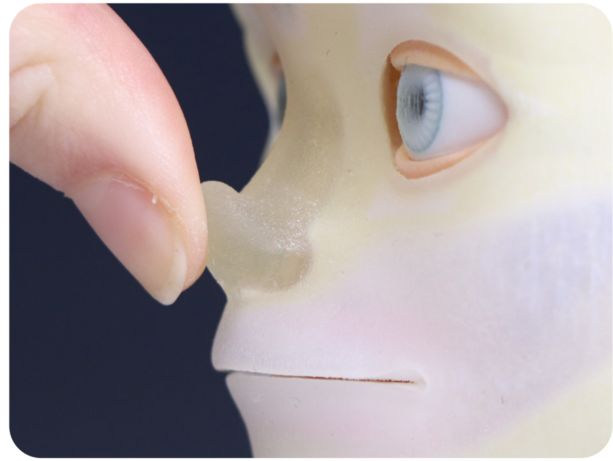


Figure 89: Jeffrey Nose Deform

Figure 90: Jeffrey Lip Deform #2

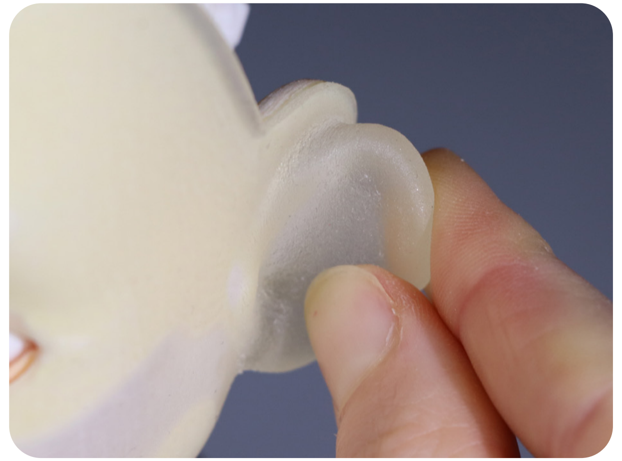


Figure 91: Jeffrey Ear Deform

Figure 93: Jeffrey Blender Screenshot #5

5

DISCUSSION.

This chapter outlines the limitations of the research conducted in the area of technical restrictions and highlights opportunities for further research development within MMP technology relating to this thesis.

LIMITATIONS .

Vero breakage and wear

100% Vero material offers a rigid part quality which is used in this research to provide a concrete form to parts when an unchanging form is required for proper function. The downside of its material quality is that its low ductility makes it prone to shattering when under stress, shown in the breakages of parts while freeing them from enclosed support. The print surface quality of parts coupled with its brittle nature also produces frictional wear, which is shown in experiments.

Agilus tearing

With current 3D printing technology allowing designers to change the density of individual parts of an assembly, this opens up many opportunities in digital manufacture. Unfortunately, in the testing of this application, the material I had access to, though far more ductile than Vero, does not measure up to the deform capabilities of the silicone used in Corpse Bride, resulting in tearing shown in the corners of the mouth.

Visual qualities of clear Agilus

Throughout the testing of this proof of concept, the clear Agilus was great in that its translucent quality allowed better analysis of test experiments. However, in production, the character's unnatural skin may distract from the story and harm the audience's engagement.

Cleaning / freeing

The support material's ability to crumble and be degraded with warm water is a huge advancement from other forms of 3D print support. However, with the complexity of and the tolerances involved in this research's application cleaning the full head print was tedious and time-consuming, with part freeing becoming a recurring issue in successful function.

OPPORTUNITIES .

Voxel control

This research changes colour and materiality by individually assigning them to whole parts of an assembly. Voxel printing capabilities of the J850 mean that materials differing in colour and density can be assigned in different combinations to the voxel structure of a part. What this means for materiality is that composite materials can be created, made up of materials of different densities positioned in varying structures throughout the part. These composite materials could help increase the strength, ductility and resistance to friction of Vero parts used in this research. For example, Vero and Agilus could be thinly layered like plywood to create a laminate, or Agilus voxels densely scattered within a Vero part. In combination with coloured Agilus this can allow detailed colour maps of different colour changes of the face to be embedded into the print, resulting in a morphable face with the colour qualities of the face prints shown by Laika. Along with the Cuttlefish Voxel placment system developed by

Digital Anatomy Printer

Stratasys offers a Digital Anatomy Printer (DAP), which can 3D print representations of human anatomy. The print materials used by the DAP mimic the materiality of the human body, including bone, muscle tissue, and skin. Prints materiality is used to accurately practice real-world tasks of an operation, from bone sawing to stitching skin. The skin material used by the DAP is far softer and stretchable than the Agilus material this research had access to, which could offer less resistance while posing and avoid tearing.

OPPORTUNITIES .

Coloured Agilus

As of 2022, Stratasys has released coloured Agilus materials, offering the ability to colour parts in the same way Vero parts are in this research. This opens up the opportunity to give puppets opaque believable skin tones while keeping one step physical manufacture, resulting in a puppet better suited to connect with the audience.

Liquid support

Stratasys offered the university an early iteration of liquid support capabilities for beta testing. This uses a liquid instead of the gelatinous material seen in this research to support parts in free space while printing, resulting in the liquid support being washed away with ease and parts freed without force. A trial was completed during this research to liquid support the difficult lateral shift gearset while printing. It was unsuccessful, but due to the parts of the assembly not meeting the liquid support system's required dimension and tolerance criteria, along with it being in its early stages of development, this was expected. Further development of this could result in pre assembles mechanisms being far easier to articulate after printing.

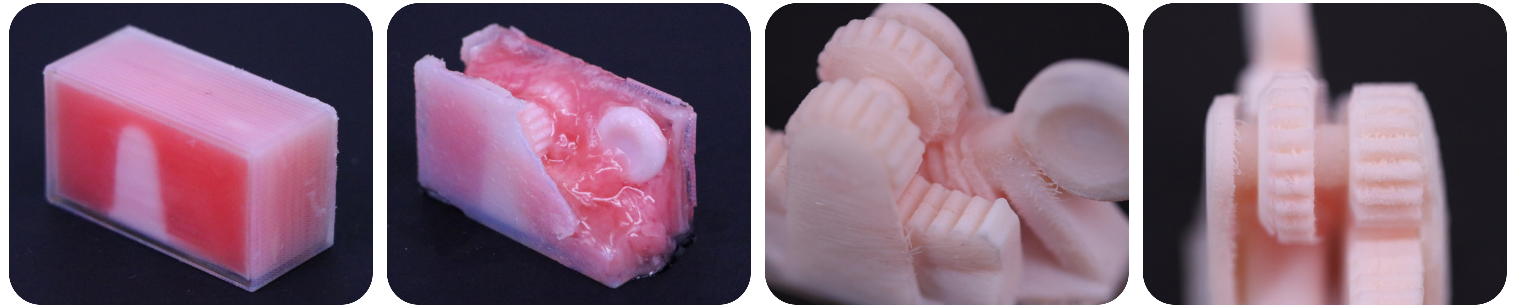


Figure 94: Gear Rack Liquid Support Test

Figure 95: Jeffrey Blender Screenshot #6

6

CONCLUSION.

A summary of the research.

INDUSTRY INTEREST.

After reaching out to Laika Studios, asking for permission to use the image used in the precedent review and having it granted, including images of Jeffrey in my original email. I received separate contact from Brian Mclean, Academy Award Winner & Director of Rapid Prototyping at Laika, expressing interest in my research, and wanting to learn more about it.

CONCLUSION.

This research uses emerging technologies and iterative experimention to further develop an art form over 120 years in the making, (Maselli, 2018) that, despite its age, has stood the test of time and is continually developing. Though the methods of manufacture and posing have greatly advanced, the tangibility of the real sets photographed under real lights continues to offer an atmosphere that may never be replicable by any other means, (Yekti, 2015). The necessity of physical manufacture and posing coupled with the complexity of the face and other complex morphing objects push those in the industry to seek out the very latest method of manufacture to push the boundaries of what is possible to be stop motion animated. It is for these reasons that new advancements will continue to be made. Taking inspiration from the best the industry has to offer, this research blends methods of posing and repurposes the existing use of these technologies already used in stop-motion, altering the outputs from 3D prints to a 4D print, with its ability to change shape over time. The expression change that this ability affords is exhibited by Jeffrey, who proves that a single 3D print can indeed be brought to life. Though not perfect in his current iteration, his digital design and manufacture offer quick iterative experimentation that can have him fully articulated in no time. The introduction of the worm gear to the system offers incremental control demanded by stop-motion and, through development by a team including animators and people more mechanically inclined than myself could see Jeffery ready to be the star of his own movie in no time.

LIST OF FIGURES .

All figures not cited are produced by the author.

REFERENCES .

Brian Mclean, AT&T Developer Program. (2016). THE ART AND SCIENCE OF LAIKA. Retrieved August 2, 2021, from https://www.youtube.com/watch?v=1NGeGcV9dXw&t=22s

Frankel, L., & Racine, M. (2010). The Complex Field of Research: For Design, through Design, and about Design. DRS Biennial Conference Series. https://dl.designresearchsociety.org/drs-conference-papers/drs2010/researchpapers/43

Mike Goroway, Laika wins technical award from the Oscars for pioneering 3D printing in animation. (2016). 3ders.Org. Retrieved August 3, 2021, from http://www.3ders.org/articles/20160111-laika-wins-technical-academy-award-from-the-oscars-for-pioneering-3d-printing-in-animation.html

Mackinnon & Saunders Ltd. (2022). Retrieved July 6, 2022, from https://www.mackinnonandsaunders.com/company-history

Maselli, V. (2018). The Evolution of Stop-motion Animation Technique Through 120 Years of Technological Innovations. International Journal of Literature and Arts, 6(3), 54. https://doi.org/10.11648/j.ijla.20180603.12

Matsumoto, D., & Ekman, P. (2008). Facial expression analysis. Scholarpedia, 3(5), 4237. https://doi.org/10.4249/scholarpedia.4237

Mackinnon & Saunders, Page to puppet on Vimeo. (2005). Retrieved July 6, 2022, from https://vimeo.com/190848344?embedded=true&source=vimeo_logo&owner=18118399

Yekti, B. (2015). Comparative aesthetic study between three-dimensional (3D) stop-motion animation and 3D computer graphic animation: Towards physicality and tactility, perfection and imperfection. 2015 3rd International Conference on New Media (CONMEDIA), 1–7. https://doi.org/10.1109/CONMEDIA.2015.7449143