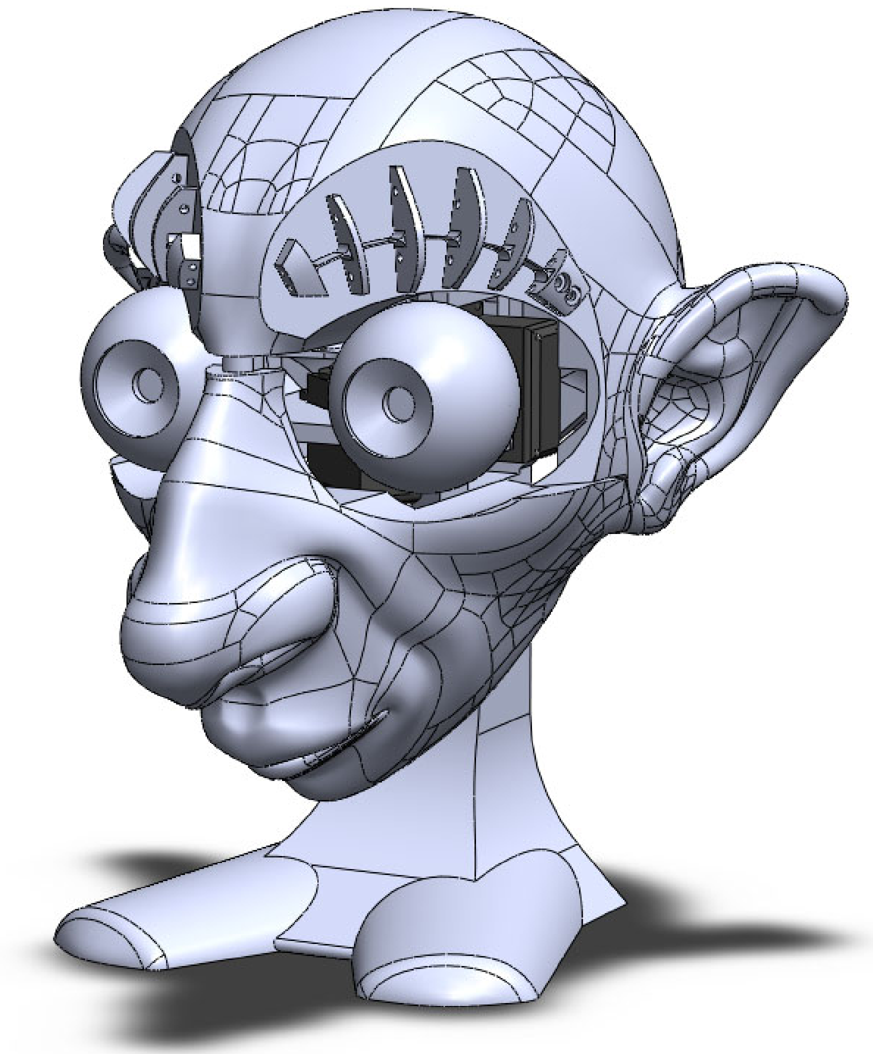
Study of 3D-printed Mechanisms for Animatronics



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1 Abstract

In this project we tested the uses of Additive Manufacturing for building an animatronic face. The objective was partly to gain a basic understanding of the processes involved with AM techniques and partly to build a testbed for further research in the area. A 3D-printed face was build along with movable eyes and eyebrows that allows for a servo-control system to be added later on. However, the final assembly was never made due to time constraints.

2 Introduction

The advancements in robot technology is bringing robots out of the shielded environments and into the open, where interaction between humans and robots are ever more important. This has given rise to the field of Human-Robot interaction, where studies are made in the means of communicating intuitively from robots to humans. Given the everyday need for humans to read the mood of our fellow beings before engaging in interaction, time and evolution has made us rather specialized in both expressing ourselves and reading other peoples body language and facial expressions. As this comes natural to us, without effort, replicating such expressiveness in mechanisms could provide a good basis for improving human-robot interaction. However, due to the complex nature of humans, replicating everything is optimistic at best. Therefore studies are made for determining priority on certain ways. Animatronics is a field of mechatronic design where the primary focus is to achieve suspension of disbelief in an audience, convincing them that the animatronic is a ‘living’ and thinking organism. The suspension of disbelief is achieved partly by animators puppeteering the mechanism in a way that appears alive and empathic ([5]) and partly by designing the mechanism to emphasize the desired persona. The field of animatronics has been focusing almost exclusively on arousing empathy in an audience for more than 50 years and while their medium is often movies, TV or theme parks, the same ideas could be applied to robotics. By the recent rise of additive manufacturing techniques, building unique mechanical constructions is now easier than ever.

3 Motivation

The motivation for this project is twofold. First, to build the basis of a demo model for DTU Fablab. This model should consist of elements produced by additive manufacturing (AM) using a wide range of printing techniques in order to showcase the different possibilities at Fablab. Secondly, to establish the basis for (i) constructing mechanical elements using AM, (ii) designing animatronics specifically for additive manufacturing that brings ‘added value’ by means of the technique and (iii) constructing and assembling AM parts into an animatronic mechanism that is able to move and trigger the interest of an audience.

4 Theory

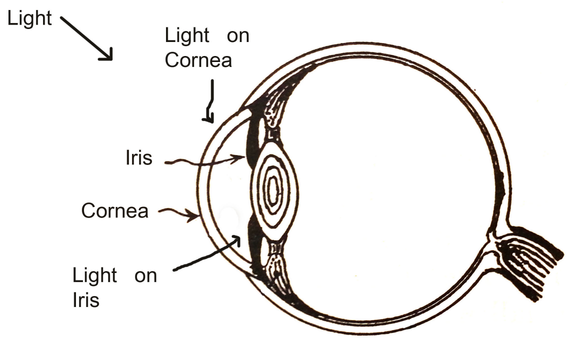
4.1 Planning the basis

Prototyping using 3D print techniques allow for much quicker feedback than traditional manufacturing, and enables a more iterative design process. While the easy and quick feedback may encourage a rather lazy approach to engineering design, certain aspects are to gain from this approach as well. When approaching a new subject that is either too complex to manage or isn’t related to an exact science, it can be difficult to start out analytically. In this study the iterative process has been applied to investigate printing techniques that weren’t previously proven and only by practical tests could be deemed functional for the course. After the initial proof of concepts had been made, an analytical approach could be taken for further enhancements.

By the words of two of the grandfathers of animation: “Through a change of expression, the thought process was shown” ([5]) it is stated that facial expressions are a way of showing inner thoughts. Applying this to robotics, the need for facial features is obvious, when interacting with humans.

4.2 Expression of the eyes

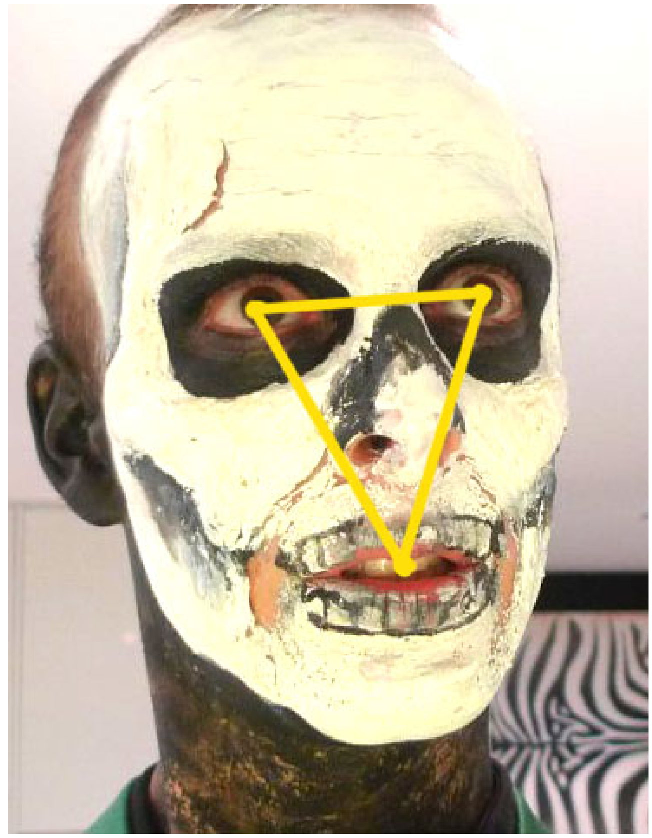
The most important feature of a face is the eyes ([1]). Getting them “right” can breathe life into almost any inanimate object. However, succeeding at this is no small feat and includes both the visuals, the mechanics and the way they move. The depth of the eye has been found to be very important. A simple painted sphere will always look wrong, no matter how well it is painted. In a human eye the iris is flat behind the cornea. Due to the refraction of light through the cornea, the iris seems to catch the light on the side opposing the lightsource as seen on Figure [below]



This is an important point when making a fake eye. From Computer Animation it is found that we can emphasize the depth even further by letting the iris point slightly inwards towards to center of the eye. This will give an even greater highlight on the iris, facing away from the lightsource.

Furthermore, having a cornea that extends slightly from the sphere of the eye brings a another very focused highlight on it's surface facing towards the lightsource. This combination of opposing highlights have been found to highly improve the interest of the eyes.

As for the motion of the eyes, when humans look at an object, they tend to jump between different points of interest. The motion inbetween these focuspoints are quick enough to hardly notice. Jumping between focuspoints in this regard is usually referred to as eyedarts and works as an underlaying motion when looking at something. The actual pattern of such eyedarts varies but certain well known patterns can be used as a basis. Ie: When greeting someone, looking at their face, normally we tend look back and forth between their eyes and occasionally down at the mouth in multiple quick successions. This makes our eyes move around in a triangle, usually horizontal and occasionally down and up.



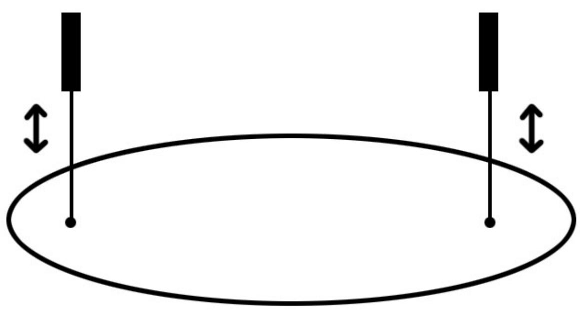
The only exception to this pattern is when tracking a moving object, where the eye moves in a smooth line.

To produce an eye that corresponds to these guidelines there are certain requirements. First, the shape of the eye needs to be printed, where the sphere of the eye, cornea and iris should be in different colors and materials. The cornea needs to be transparent in order for the iris to be seen through it. The motion of the eyes should preferrably be controlled by quick and precise actuators, where the specific motion pattern can be programmed into the control board.

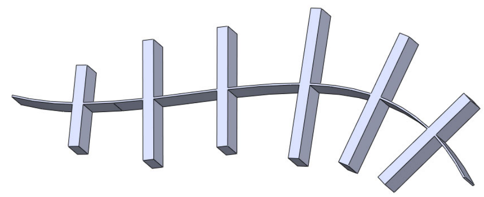
4.3 Mechanics of the eyebrows

The expression of the eyes is a combination of both the eyes and the surrounding shapes - eyebrows, eyelids and the muscled surrounding the eye. For this project the timeframe only allows for a selection of these. As eyebrows are very expressive along with being interesting from a mechanical point of view, it was chosen to focus on the eyebrows alone.

While eyes are almost rigid and moves as such, the eyebrows are highly flexible and can take many shapes, which is complicated to replicate mechanically. Looking back to animatronics ([2]), mechanical eyebrows can be made in many ways. Many of which make use of separate points along the eyebrow moving independently up/down. These are then covered by a layer of silicone to add the organic appearance and combine their positions into a single curve-shape. While the results are fairly good, the use of silicone surfaces is beyond the scope of this project. Alternatively a single rectangular plate can be used by attaching it at both ends to a point that can move up/down while allowing rotation at the fixed points.



This gives up/down motion as well as rotation of the plate. Such a solution could work but wouldn't draw any benefits from additive manufacturing as well as restricting the shapes to linear. A third alternative, also inspired by animatronics is a mechanism mostly used for tails or tentacles. It is a herringbone structure with a bendable centerline and a number of crossbars evenly spaced along it's length. Each side of the centerline is then threaded through holes in the crossbars, attaching the thread in one end. Pulling the thread from the opposite end will then apply a momentum on the centerline from the crossbars, thus bending the structure. Provided such structure could be made by AM as a single print, added value could be achieved by embedded functionality. It was theorized that further control of the bended shape could be established by a combination of varying the height of the centerline, varying the distance of crossbarholes to the centerline and applying stops between crossbars, thus restricting their rotation to a certain angle and allowing for underactuated motion.



By further investigations of the needed eyebrow shapes, the herringbone design could be approximated with the above variables, using the theory of strength of materials: The curve should be estimated by looking at the segments between each crossbar individually. The sections can be seen as a beam that is fixed in one end with an applied momentum coming from the prior section. Given the low stiffness of the thread itself we can assume that it's influence can be neglected. Starting from the end where the thread is attached, the momentum around the centerline is calculated by the stress on each thread times the distance from the centerline. This is then used to calculate the momentum around the clamped end as well as the angle of deflection. Running through each section, the shape of the curve can be drawn by the angle of deflection applied to the length of the section. Arranging this as a function of the tension in each thread, the construction can be understood analytically. Adding stops to the equation gives a maximum angle of deflection to certain sections, independent of the tension. Varying the distance of the holes in the crossbar to the centerline changes the amount of deflection for a maintained value of tension in the threads. Looking back at the list of facial expressions (fig?), such a system could provide a wride range of motion with only two actuators.

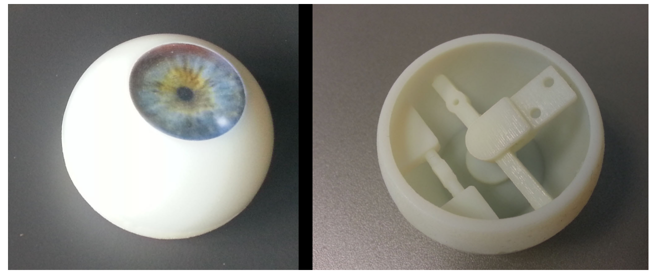
Designing the eyebrows proved much harder given the elusive nature of their mobility. The idea required that a bendable centerline could be printed. As Fablab does not have a printer that allowed for printing with soft materials, the theory was that a very thin wall of material could bend, despite the material being rather stiff (Move this to theory section?).

5 Process

The form of the complete setup was initially decided to be a head bust. This would allow for a wide range of mechanical features in a single object. However, due to time limitations, priority was given to the eye region, which is the most expressive part of the face. Having decided on the form, next step was to find an actual design that would allow for the widest span of AM techniques to be applied. Furthermore, given that Fablab does not have any immediately available techniques for printing stretchable parts, the design needed to work without. Eventually the design was chosen based on an existing 3D model of a stylized human head made by Jakob Welner. The 3D head had been modelled in Autodesk Maya as a polygon mesh. The model was then scaled to the desired size and converted to the IGES format to import it into SolidWorks, which is more suitable for mechanical design. The imported head part was then hollowed out and cut into sections so that a suitable manufacturing technique could be applied to each piece individually. Rough placeholders for eyes, eyebrows and mount were put in place to get a feeling for the final result. From here each element were worked through individually, tweaking the adjacent elements accordingly. Each part were categorized and listed with their requirements.for AM, in order to make use of as many techniques as possible. Every part were furthermore designed for the particular printer. Parts with complex geometries and overhang were targeted [insert print type for Blueprinter/zcoorp, object fully embedded in the material.]. Big and simple parts were suited with a lower resolution printer using cheap materials and intrinsic mechanical parts were aimed for the higher-resolution multi-material printers allowing for such. After assigning each part to a printer, care was taken to further enhance the print by designing to the extent of each printer's capabilities.

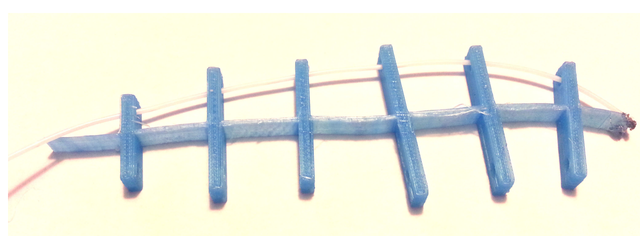
5.1 Eyes

For the eyes to be able to look around, they needed to rotate on 2 axis about their center. They were intended to be controlled by 2 servo motors, one for each axis, each servo connecting to both eyes. For the eyes to rotate on 2 axis, a gimbal needed to be placed in it's center, the design of which was inspired by an animatronic head shown in Gustav Hoegens Animatronics showreel 2011 ([2]). By printing the eyes on the Stratasys Objet 30 Pro (See Appendix for specs) the gimbal and eye could be printed as a single file, while still being able to rotate. This was achieved by designing the mechanism with 0.1mm between each part, though printing it as a single unit. To optimize the design and save material on the Objet, the mount and gimbal was designed to be fully contained inside the eye with the ability to rotate out of the shell and attach to the head mount. This lowered the overall height of the object, thus saved time printing as well as use of material. As the Objet only prints one color, the iris was designed as a separate part that could be snapped into a fitting on the front of the eyeball. The iris was then designed somewhat according to the previously mentioned theory where the iris bends inwards to emphasize depth. The iris was then textured with an image of an iris found on Google and printed on the Zcoorp 650 which allows for colorprints. The iris was then coated with an adhesive based on an ABS poly suspension in acetone and snapped into place on the eyeball. The cornea proved difficult as the lens-shape extending from the spehere of the eye wasn't easy to achieve. Filling in nailpolish was initially test but failed.

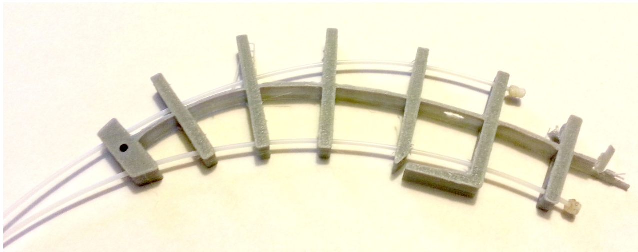


5.2 Eyebrows

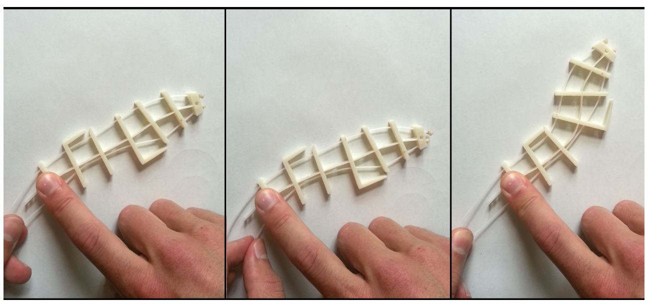
Initial tests were made for whether walls could be printed thin enough for them to bend without entering plastic deformation. For this to have any strength at all the segment would need to have either a height or width, thus limiting the degrees of freedom possible. Tests were initially conducted on the Ultimakers, enquiring the smallest possible wall thickness. Parts were tested both lying down (Thinnest on the z-axis) and standing up. With a nozzle diameter of 0.4mm on the Ultimaker, which is also the minimum of wall thickness, the immediate thought was to model a part with a wall of 0.4mm. However, when slicing the part in Cura, the wall would disappear and random connections between the crossbars would be drawn instead. Extending the wall thickness to 0.5mm solved this issue and a part was printed on the Ultimaker. It turned out that 0.5mm walls worked well for bending,



Despite a mediocre print job where it seemed Cura was still struggling with the wall thickness It served as proof of concept and the design idea was accepted. Further tests were made for varying distances between the holes and the centerline, along with added stops.



The tests were successful, however, the centerline was fragile and the PLA too crisp for multiple bends. Running a new test on the Stratasys Mojo proved much better. The slicer in the Mojo software turned out to produce a much cleaner path along the centerline. Furthermore the use of ABS plastic instead of PLA allowed for even more flexibility. Different placements of the holes were tested simultaneously by placing several holes in each crossbar and trying out different ways to connect them.



To allow for printing of a curved centerline it would have to stand up. In contrast to tentacles used for tails, producing such a herringbone design on a 3D-printer would only allow for a bend on a single axis given the height of the centerline. The brow structure was then designed to lie against a flat cutout on the face. This would both serve as saving support material when printing, increasing stability of the part and lowering printing time. To still follow the curvature of the face the brow was designed with a curved top.

5.3 Mount and shell

The mount was continuously refined along with the shell while working on the other parts. The shell, now separated into different pieces of the original head-design, was fixed to the mount. Idea was to have a mount that could stand by itself and serve as the test bed while working on other parts. The lower part of the face would then slide onto the mount. The forehead was shaped to fit the eyebrows with 2 holes on the outer end for fixing them with screws.

5.4 Verification

Designing parts for AM requires a certain high tolerance for the most part. Through this project the designs have been made for a guestimated tolerance, yet never verified. Potential ways of verifying 3D-printed objects include "In-process 3D geometry reconstruction of objects produced by direct light projection" (David Bue Pedersen), where each layer of the AM process is photographed and used to construct a 3D model of the actual product. This product can then be compared to the original 3D model and a variance can be calculated.

5.5 Complications

During the process several printers failed during print. There was a power outage in the middle of a larger 30hour print job, which then had to be reset and the MCor, which had been assigned with the task of producing the forehead, never produced anything.

6 Discussion

Additive manufacturing is well suited for producing the unique and intrinsic designs needed in a mechanical face. Added value can be achieved by embedding features in single parts, skipping assembly and reducing required size which again gives room for further actuated parts. Working with ABS and PLA as the most flexible materials available greatly limits the capabilities when working with facial expressions. Due to the complex nature of facial expressions, many FACS modules ([4]) / actuators can influences the same areas simultaneous, which is exceedingly difficult to design using rigid elements only. There are many ways these techniques can be applied and there is a lot of room for further improvements. Despite Additive Manufacturing being a fairly old technology, it is still in it's infancy and many further improvements can be made. The possibilities are grand!

7 Conclusion

This project has proven that animatronics can be produced by Additive Manufacturing and that the technique allows for added value in terms of compactness of design and ease of construction. Several techniques were proven successfully and a basis was made for future research in the field. Due to timeconstraints and several unforseen obstacles along the way, the head was never finally assembled. However, CAD-drawings of the model have been made and given a few further adjustments and time to print the new parts, it should be possible to produce a model which can look around by rotating it's eyes, as well as move the eyebrows in several ways, by tightening or loosening 2 strings.

The final product of this project ended up as so:

8 Future Works

The product of this project can be used as a testbed for future research on designing expressive mechanics by AM. Adding eyelids, actuated chins, jaw and neck could provide a much broader span of expression along with challenging design for AM further. The recent success of printing with polyurethane rubber could be applied as flexible skin to replicate the function of silicone surfaces in animatronics. Being able to print it directly would furthermore allow for added value by producing precise patterns and thickness. Such control could allow for a part that can stretch, bend and deform in very specific ways, which would be nearly impossible to replicate by casted silicone.

The field of Human-Robot interaction has found that there is a certain relationship between a robots appearance becoming more anthropomorphic and humans inclination towards interaction with it. This is only true up till a certain point, where the robots starts to resemble humans too much and the so called Uncanny Valley appears [3]. Further studies could be made in this field in order to narrow down the most powerful way of communicating.

Due to mechanical restrictions there is almost always a need to prioritize the ability to convey different expressions in terms of number of actuators. In 1978 Paul Ekman and Wallace V. Friesen published an article on the Facial Action Coding System (FACS) ([4]). By using FACS the face is divided in a number of modules, somewhat relating to the muscles underneath. By combining these modules in different ways, all expressions should be possible to replicate. This gives a theoretical number of actuators needed for a fully articulated face, which could be applied to a mechanical face as well.

References

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[2] Gustav Hoegen. Animatronics Showreel 2011, 2011. 4.3, 5.1

[3] Masahiro Mori. The Uncanny Valley, 1970. 8

[4] Paul Ekman Rosenberg and Erika L. *What the Face Reveals: Basic and Applied Studies of Spontaneous Expression Using the Facial Action Coding System (Facs)*. Oxford University Press, 1997. 6, 8

[5] F. Thomas and O. Johnston. *The Illusion of Life: Disney animation*. New York, disney edition, 1981. 2, 4.1

9 Appendix

9.1 DTU Fablab Printers

- MCor Iris: LOM printer (ref?) using plain white paper. Cheapest material and no need for support structures as the model is embedded in the stack of papers. Final product can be hardened by soaking in glue or other liquids that stiffen
- Stratasys Objet 30 Pro: [Type?] Prints in ABS?. Smallest tolerances available. Prints support structures in a soft material that can later be removed by high pressure water gun. The precision of the Objet enables embedded mechanics printed as one part, allowing otherwise impossible mechanisms
- Zcoorp 650: [Type?] Prints in plaster powder. No need for support structures as the part is embedded in powder. Can print color.
- Ultimaker: [Type] Prints in PLA. Relatively cheap material, cheap hobby printer while allowing fairly high level of precision. Open design that can be customized to fit special needs. Arduino based with full access to the firmware. Uses gcode files and allows the user to decide which slicer software to use.
- Stratasys Dimension 1200: FDM printer. Strong parts.. blablabla
- Stratasys Mojo: FDM priner. Small print area and lesser resolution than the Dimension 1200. Otherwise same principle.
- 3D maker: FDM printer
- Blueprinter: SHS printer