

Diplomarbeit

A Reflective Mechanical Media Façade Technology

Alex Falkensteiner

Institute of ComputerGraphics and KnowledgeVisualisation, TU Graz

www.cg.v.tugraz.at



Abstract

This thesis is about developing of a display device technology for house façades. Its concept shall enrich the variety of already existing solutions and focuses on cost-efficiency and easy integration. These aspects make the device available for a broad public. Weaker focus is on the aspects of resolution, colour depth and refreshing rate. Neglecting them also leads to strong advantages in the applicability and the low resolution can easily be compensated, for example with special pixel configurations. This thesis approaches topics mentioned above and demonstrates the potential of the concept.

The paper will be divided in three parts. The first part will cover the related work in this field and diverse products as well as research already conducted on this topic. The legal situation of public screening is shortly explained as well. In the second part, the development and realisation of several prototypes is described in detail. Finally, the third part will contain the theory of image processing for the operation of the device is provided and examples of possible operations are presented.

In the course of this work, simulation software for testing and demonstrations was developed, several prototypes were constructed and tested, two prototypes were ultimately refined and a parametrical model of an extended prototype was written.

Keywords: Media Facade, Mechanical Display Device, Reflective Display Device, Low Power Display Device, Low Color Depth Display Device

Zusammenfassung

Diese Arbeit beschäftigt sich mit der Entwicklung einer Technologie für Anzeigevorrichtungen für Hausfassaden. Das Konzept soll die Vielfalt der bereits existierenden Lösungen bereichern. Hauptaugenmerk wird auf die Kosteneffizienz und die einfache Integration gelegt. Dadurch soll die Medienfassade für eine breite Öffentlichkeit verfügbar gemacht werden. Auf die Aspekte Auflösung, Farbtiefe und Bildwiederholfrequenz wird weniger Wert gelegt. Die Vernachlässigung dieser Aspekte bringt auch wichtige Vorteile in der Anwendbarkeit mit sich. Weiters ist die niedrige Auflösung nebensächlich, wenn mit spezieller Pixel-Konfiguration ein noch besserer Effekt erzeugt werden kann.

Dieses Dokument ist in drei Teile aufgeteilt. Der erste Teil beinhaltet themenbezogene Arbeiten in diesem Bereich und verschiedene Produkte, sowie Forschungen, die zu diesem Thema betrieben wurden. Die Rechtslage solcher öffentlicher Anzeigeflächen wird ebenso kurz erklärt. Im zweiten Teil wird die Entwicklung und Realisierung von Prototypen im Detail beschrieben. Schließlich wird die für den Betrieb der Anzeige nötige Bildverarbeitungstheorie behandelt und Beispiele von möglichen Anwendungen vorgestellt.

Im Zuge dieser Arbeit wurde Simulationssoftware für Tests und Demonstrationen entwickelt, einige Prototypen wurden gebaut und getestet, zwei davon wurden schließlich verfeinert und ein parametrisches Modell eines erweiterten Prototypen wurde erstellt.

Schlüsselwörter: Medienfassade, Mechanische Anzeige, Reflektive Anzeige, Niedrigstrom Anzeige, Anzeige mit niedriger Farbtiefe

Statutory Declaration

I declare that I have authored this thesis independently, that I have not used other than the declared sources/resources, and that I have explicitly marked all material which has been quoted either literally or by content from the used sources.

Eidesstattliche Erklärung

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Chapter 1

Introduction

1.1 Motivation

During the last years there has been a rise in installations of huge screens. These display devices mounted on a building, as they mostly are, are called *media façades*. The purpose of such graphical presentation gadgets in big scale is generally advertisement, but they are also used for the spreading of information and often also for artistic purposes. Some people may think that it is a waste of energy, others possibly argue that the townscape suffers from too many and too transient colour arrangements or inappropriate motifs. The great possibilities, however, should not be neglected because individuality and innovative design are of great value. It is only fair and smart to develop a technology for the building of a media façade everybody can enjoy. Public space can turn into a huge artistic playground while individually and carefully decorated homes are a great increase to the beauty of a town. This work, however, does not lose sight of the importance of the user acceptance and tries to find the best compromise between a shiny video wall and a discreet decoration.

1.2 Conceptual Formulation

The already existing types of media façades (for a detailed listing refer to Section 2.2) are developed for different purposes. The technologies used and the out-coming products always meet special criteria and each has its characteristics. The most relevant characteristics are:

- Who can afford it?
- What is the desired quality (pixel resolution, colour depth, brightness, contrast, reaction time)?
- How much energy is required?
- Are road users distracted or the townscape distorted?
- Can it be mounted easily and at any time and structure?

It is necessary to focus on a subset of these criteria because optimizing one of them always leads to a trade-off for an other criteria. A compromise has to be accepted and special criteria have to be declared before building such a display screen. For this project the constraints are set as follows.

Who can afford it?

Definitely not only commercial clients, but everybody should have the technology available for his own house. The price per pixel (or per square meter) will have to be very low, so that demand and thereby numbers in production increase. The design must fit standard fabrication methods, so that with increasing production numbers the price can be reduced again. The goal is to be able to build a display for one Euro cent per pixel.

Energy requirement

A hard restriction is set from the very beginning: In the non-transient state no energy must be consumed. This is not only obvious for sustainability reasons, but it is also a cost factor for the end user. The device will use electrical energy only when changing the output of the display device. It is also understood that because of this constraint the pixels are designed reflective in the first place. Pixels do not emit light on their own.

What is the desired quality?

The strict limits in fabrication costs lead to the inevitable reduction of some quality claims. The reaction time is the least

important aspect. It goes hand in hand with the energy issue and is part of the concept, as no transient media is meant to be shown. The colour depth is low as well, but there are other techniques to compensate it (see 5.1). The contrast value is customizable and only limited by the used material and tint. Regarding the pixel resolution the display can be scaled freely within an upper and a lower limit resulting from the mechanical behaviour. The development described here focuses on pixels being $80 \times 80 \text{mm}$ in size and with minimal distance between them. The brightness depends only on the conditions of the environmental light as the display is reflective. The use of mirrors highly increases the brightness, yet the legal situation has to be considered (see Section 2.4).

Are road users distracted or the townscape distorted?

Due to the wish that everybody should have the possibility to mount it on his own house some rules must be considered in order not to attract too much attention. Unlike Las Vegas for example, most cities would not allow every house to have a huge shiny façade showing random motifs. Also there are laws concerning the safety of road users which prohibit possible danger in certain cases. Section 2.4 shortly describes these restrictions.

Looking at the differences between existing solutions (Chapter 2) and the desired outcome of this work, one can see why more research and development is required in this area. This concept is affordable for private and commercial clients and still offers good and adaptable quality. It is eye catching but does not distract because it is slowly changing. It is an upgrade for the townscape but does not distort it because no additional light sources are installed. It consumes a minimum amount of electrical energy and finally it is kept simple in order to allow easy mounting regardless of the façade's peculiarities.

Chapter 2

Related Work

2.1 Display Technology Fundamentals

In this section some technologies are mentioned which could be relevant to build the desired display. A pixel does not need to glow, but instead has to change its colour. Therefore it was clear that the pixel itself, meaning the material seen by the observer, has to change its surface in a way. Like this the reflecting characteristics change in some way. The first thoughts on which technologies could be used are listed here.

Liquid Crystals

Liquid crystal displays use the light modulating properties of liquid crystals by which a so called liquid crystal cell is turned from transparent to non-transparent (i.e. black) by applying a small voltage. Without using background light an LC cell does not emit any light but can still be used as a monochrome reflective pixel. A grid of liquid crystal cells can scale to a huge façade display. The contrast values and the cost-performance ratio still have to be evaluated. A related product is described in Section 2.2.2.

Light Emitting Diodes

This technology is widely used for big display screens. Three basic colours make up a pixel with very high colour depth and fair brightness. Though, the cost factor is still an important issue and the power consumption has to be considered as well. Find examples of LED driven devices in Section 2.2.1.

Light Polarization Filter

By filtering polarized light and thereby block certain polarized light waves it should be possible to build a configuration which is able to change the filter characteristics in a way to change a pixel's colour. For example by combining a pair of filter layers and changing the alignment between them. This approach, however, relies on mechanical movement - which again undoes the advantage of using light filters. An other disadvantage could be the limited brightness after filtering.

Nano Technology

With nano technology it is possible to have a colour-changing behaviour by looking from different angles on a material or by stretching it [WWL07]. However, the technology is an over-design for the wanted purpose and hardly possible to handle in a grid at bigger scale. The technology is also too expensive.

Mechanical Show and Hide

After these investigations it was easy to make the decision not to use any of the above mentioned technologies, but rather to invent a mechanical pixel. Either flags should be used, or prisms with differently coloured side faces which are exposed to the viewer by turning the pixel. Or, the coloured face of a wall is somehow hidden and thereby (de)activated. This is the most promising idea with the desired functionality and potential to fulfil the goals within expected costs. It is further developed in Chapter 3.

2.2 Existing Façade Displays

2.2.1 Transmissive Displays

Kunsthau Graz

The Kunsthau in Graz, Austria is an art museum and has a very special façade. It was created by Peter Cook and Colin Fournier (Realities United [Uni]). It is also called "Friendly Alien" due to its extraordinary shape. The front side, however, is even more special, because under the perspex façade (composed by 1066 uniquely rounded tiles) there are 930 neon lamps. The lamp's luminosity can individually be controlled at 20 frames/second. Still images can be displayed just as films or animations. Although the façade can not show colours, the outcome is still very impressive. A video [EEU03] and some pictures (Figure 2.1) should demonstrate its function and beauty.

Advantages:

- **Size** the device covers the hole eastern side
- **Image quality** transitions are totally fluent and even during day it is bright enough to be operable
- **Shape** unique and eye-catching

Drawbacks:

- **Resolution** the viewer should stay at least 100 meters away to be able to fully enjoy the show
- **Colour depth** no colours can be displayed
- **Mounting** every lamp has to be mounted individually and cable connections are huge in number
- **Price** the estimated price is certainly above the limits set for this project
- **Power consumption** that many and big neon lights consume a lot of energy

A very similar project – also from Realities United – has been set up in Berlin and is called SPOTS [Uni10]. Besides those two projects the company has been working many other projects somehow related to the topic.

ag4 Products

The company ag4 media facade GmbH [amfG10] has various projects and products which use LED technology to illumine a façade. Their products are designed for various applications. Mediamesh (Figure 2.2) is one of them and it is especially designed to fit big façades and still provides high resolution. The LEDs are mounted on a stainless steel grid which makes the system 40% - 90% transparent. Besides that, it is scalable in size and the power consumption is relatively low due to LED technology. The pixel density is also low, but the refresh rate is high enough to show videos.

Advantages:

- **Applicability** the system is adaptable and can be mounted on any flat or slightly rounded surface
- **Image quality** colour depth, resolution, brightness and size are scalable to meet requirements
- **Permanence** the stainless steel construction ensures long life at minimal maintenance

Drawbacks:

- **Price** ranging between 2.000 and 15.000 Euro per square meter
- **Power consumption** the more LEDs are used the more energy is constantly needed

This really is a professional product with outstanding features - but the price and the power consumption are big issues.

Projections on Buildings

Another innovation is to project images with a video projector on a wall or a building. The projected area is preferably white and flat, but with a strong projector and appropriately adapted motifs it is possible to virtually paint on any surface. A technique called *raypainting* uses the given architecture and a video projector to enhance the given façade. Like in the example with the cathedral (Figure 2.3) all the structural details are still recognisable but with an overlay of colours and paintings. The building is virtually painted on the computer and light rays project it on the building. Another approach is to project videos on a façade which are also able to produce realistic 3D effects using the structural conditions of the building (see an example on [Med09]). The possibilities are boundless.

Advantages:

- **Applicability** the system is adaptable and can be mounted everywhere, even temporarily
- **Image quality** colour depth, resolution, brightness and size only depend on the projector
- **Visual effect** the concept has all the potential to generate diverse stunning effects

Drawbacks:

- **Power consumption** such projectors are heavy energy consumers
- **Applicability** daylight interferes strongly and good results are achievable only by night



Figure 2.1: Some impressions of the media façade on the Kunsthhaus in Graz (from www.realities-united.de)



Figure 2.2: Some impressions of the Mediamesh technology (from www.medienfassade.com).

2.2.2 Reflective Displays

Proteus Screen

The Proteus screen uses LCD technology. The display consists of liquid crystal cells of 75x75 mm. Each one represents a pixel. Such a display device costs, depending on the size, about 1800 Euro per square meter. Regarding the information on their website [Eng10] the product seems very mature and sophisticated. The pixels are powered and held by steel cables which make the installation easy and feasible even on rounded surfaces. Figure 2.4 shows the device.

Advantages:

- **Power consumption** less than 5 Watts per square meter
- **Refresh rate** videos and animations can be shown
- **Size** freely scalable up to 10.000 square meters
- **Durability** the pixels and wiring are supposed to have a lifetime greater than 10 years

Drawbacks:

- **Colour depth** only monochrome content can be shown
- **Pixel density** the grid is 100 mm spaced resulting in a pixel border of 25 mm between pixels
- **Contrast** depends on environmental light and is limited to 50:1
- **Price** 18 Euro per pixel is very expensive for a monochrome display device

This display comes very close to the requirements set for this project but in terms of resolution and power consumption there is potential for improvement. Also the wish to show colours is not covered by this technology.

2.2.3 Reflective Mechanical Displays

FLARE

The FLARE system is more like a dynamic hull than a display. Its units are tiltable metal flake bodies (see Figure 2.5) put in motion by a pneumatic cylinder system. Every flake (representing a pixel) can be tilted individually to control the amount of reflected sunlight. Even though the device only consumes power during state changes, it must be considered that the visual effects rely on constant movement (see the video [WHI08]).

Advantages:

- **Visual effect** due to the pixel's shape the visual effect is stunning
- **Power consumption** only during movement

Drawbacks:

- **Colour depth** only two pixel states with different amount of reflected light are possible
- **Loudness** the pneumatic system makes a lot of noise
- **Price** such mechanical systems are expensive
- **Mounting** the pneumatic system with its tubes needs a lot of space and a strong metal grid

Despite the disadvantages this is a good exemplar for this project.

Solar Display

This is meant to be a novel, modular, self-powered, environmentally friendly and non-intrusive display. The big innovation here is that the device is self-powered through solar panels, meaning that the pixels themselves are solar panels and drive the integrated motor independently from other power sources. The motor tilts the pixel plane on a horizontal axis upwards or downwards which changes its reflection characteristics (see Figure 2.6). The system has been installed in Linz, Austria and all the informations are accessible on the web-page [MSS08].

Advantages:

- **Power consumption** no power is needed
- **Mounting** pixels are mounted on a flexible grid

Drawbacks:

- **Price** solar panels are expensive
- **Colour depth** the pixel only changes its orientation to the viewer/sun and is not able to show colors

The concept is innovative and exemplary for the sustainable trend which makes it a very important invention. The goals set for this thesis, however, can not be fulfilled by the solar display nowadays.



Figure 2.3: These façades were 'ray-painted' during a festival in France (from flickr.com).

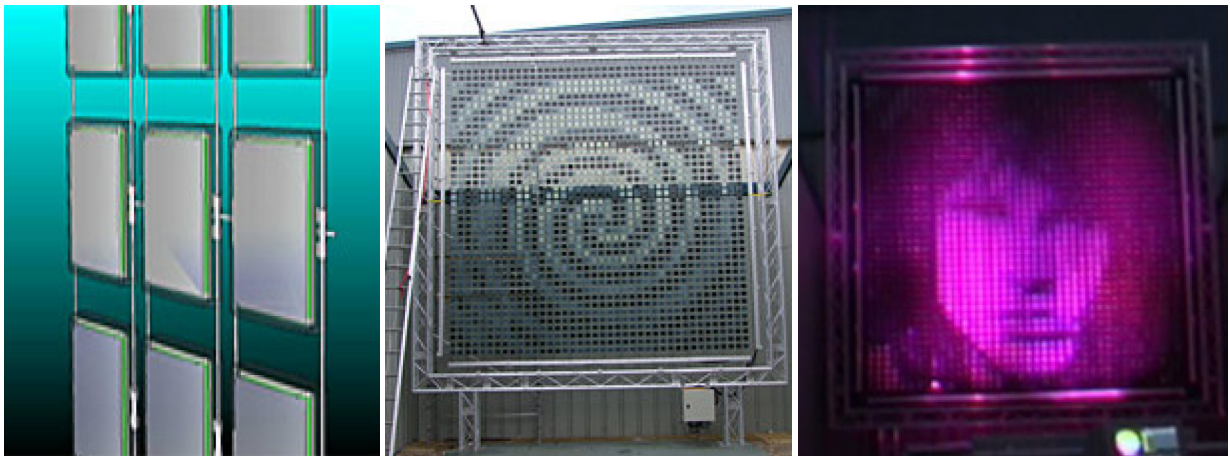


Figure 2.4: The Proteus Display: how it is mounted, at daylight and by night with illumination (from [Eng10]).



Figure 2.5: The flare display from behind with pneumatic actuators and mounted on the façade (from www.flare-facade.com/).

Flip Displays

Flip-disc/-dot [WT03] or split-flap [TM95] displays are widely used. They are seen a lot in public means of transport. The display device usually consists of a grid of flags which are somehow mounted in a bi-stable hanging and remain in one of these positions unless they are activated to turn around. The flip-around mechanism is often magnetically powered or eventually driven by a motor. Regardless of the design they are basically all very similar in terms of function. Figure 2.7 shows some examples.

Advantages:

- **Robustness** the technology is proven and long-term tested
- **Availability** there are a lot of products on the market

Drawbacks:

- **Price** the price for building really large displays is not reasonable
- **Loudness** depending on the model they can make a lot of noise

This technology comes very close to the goal set by this project but such devices were not designed to scale. Such a display in big sizes can not be driven without significant increase in cost or complexity.

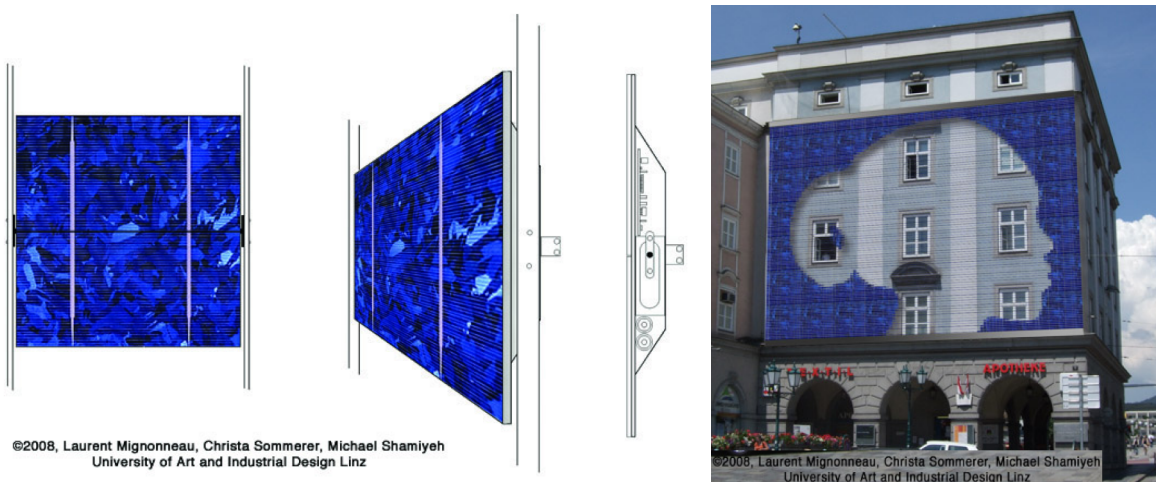


Figure 2.6: The solar display installed in Linz, Austria (from [MSS08]).

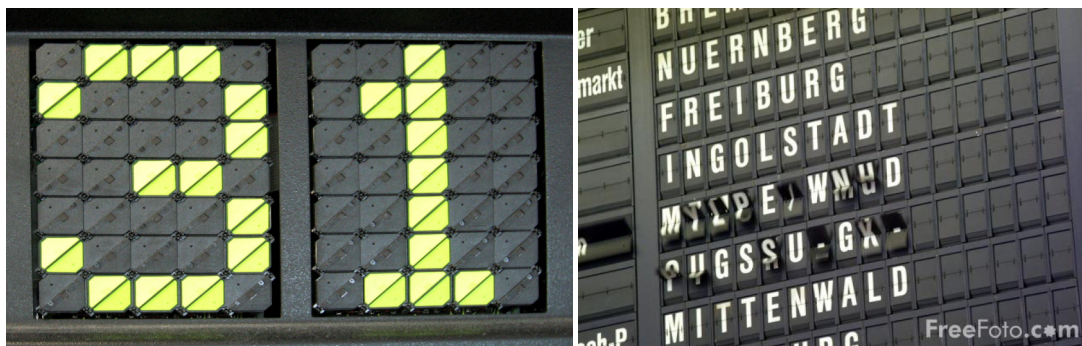


Figure 2.7: The flip-dot display is more flexible but the flip-page display can show previously defined messages in a better quality (from en.wikipedia.org/wiki/Flip-disc_display).

2.3 Other Approaches and Inventions

An Electromechanical Display Invention

This invention [VR01] describes an attempt to build a display similar to this project. For better understanding please refer to Figure 2.8. The white background (3) serves as basic colour. Translucent plastic flags (5) of different colours reveal vertically upwards to filter out certain colours subtracting them from the white background. Every pixel module has at least three such revealable flags which are proposed to be actuated by coils or a wirde grid. The degree of revealment is meant to be continuous.

Advantages:

- **Image quality** a very high colour depth is possible and pixel borders can be avoided
- **Size** the modularity allows high display sizes

Drawbacks:

- **Power consumption** the flags are not designed to stay in its position but must be powered to remain active

The explanations, however, are very sketchy and the description of the mechanical functionality deficient. Three concepts are presented but detailed information is missing. With the experience gained out of this work it is doubtful that the proposed functionality would work.

An Electromechanical Display Mechanism Invention

Four years later the same team published an invention [VRA05] for a mechanism similar to the previous one. This publication gives more insight in the particular functionality but less in the overall interplay between pixels. The Figure 2.8 shows a sketch of three pixels with the belts (1) (three per pixel) which are partially translucently coloured (cyan, magenta and yellow). The engagement bars (5) connect the belts (1) with the drive belt (4) in order to turn the coloured belt in the desired position. The pulley (2) at the front site of the display device is white and serves as basic colour. To drive the engagement bars it is proposed to assemble either Electrically Activated Polymers (EAP) or Shape Memory Alloys (SMA). As the belt to belt connection relies on friction there has to be a possibility of calibration. The authors propose that functionality but assume the engagement bars to be able to vary pressure. An other issue not considered in their work is the durability. The material for the flexible belt has to withstand UV radiation, thermal fluctuation and other environmental influences.

Advantages:

- **Power consumption** pixels stay in their position without the need for any power supply
- **Image quality** a very high colour depth is possible and pixel borders are small

Drawbacks:

- **Robustness** this load transmission relying on friction is not assumed to be robust
- **Complexity** the engagement bars need to vary pressure (must be controlled, not only switched)
- **Price** EAPs or SMAs are an over-design for a simple actuator
- **Permanence** there are too many moving parts which are fragile
- **Durability** the belt is either expensive or fragile

In theory this idea seems to be a good one but as the mechanism is so complex it is again doubtful it fulfils the goals in costs and durability.

Four- and Six-Message Systems for Electromechanical Displays

When using a three dimensional pixel and turning it around, due to geometrical reasons, the maximum number of possible messages to show without any gap between pixels is three. The three-sided prism is the most sided prism which still can be turned around its vertical axis without leaving gaps between two neighbouring prisms (see Figure 3.3). An invention introduces the possibility to do the same with a four-sided prism [How00] and with a six-sided prism [How07] (Figure 2.9). In the four-sided case the flat faces are concave which make it possible to turn one of two neighbouring prisms and still keeping them close to each other in order to prevent gaps. In the six-sided case the author proposes two extra panels which expand after rotation in order to enlarge the display area and to fill the gaps. The solutions, however, are trade-offs and there is no information on how the extra panels could be motorized. Both of the solutions are not satisfying for this project and they were redeveloped in Section 3.1.3.

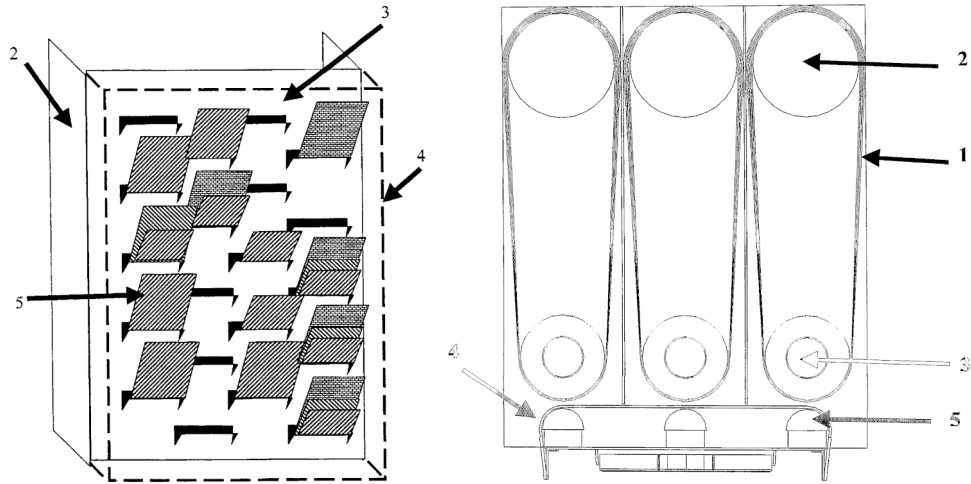


Figure 2.8: Vary's inventions of electromechanical mechanisms to change the pixels colour (from [VR01], [VRA05]).

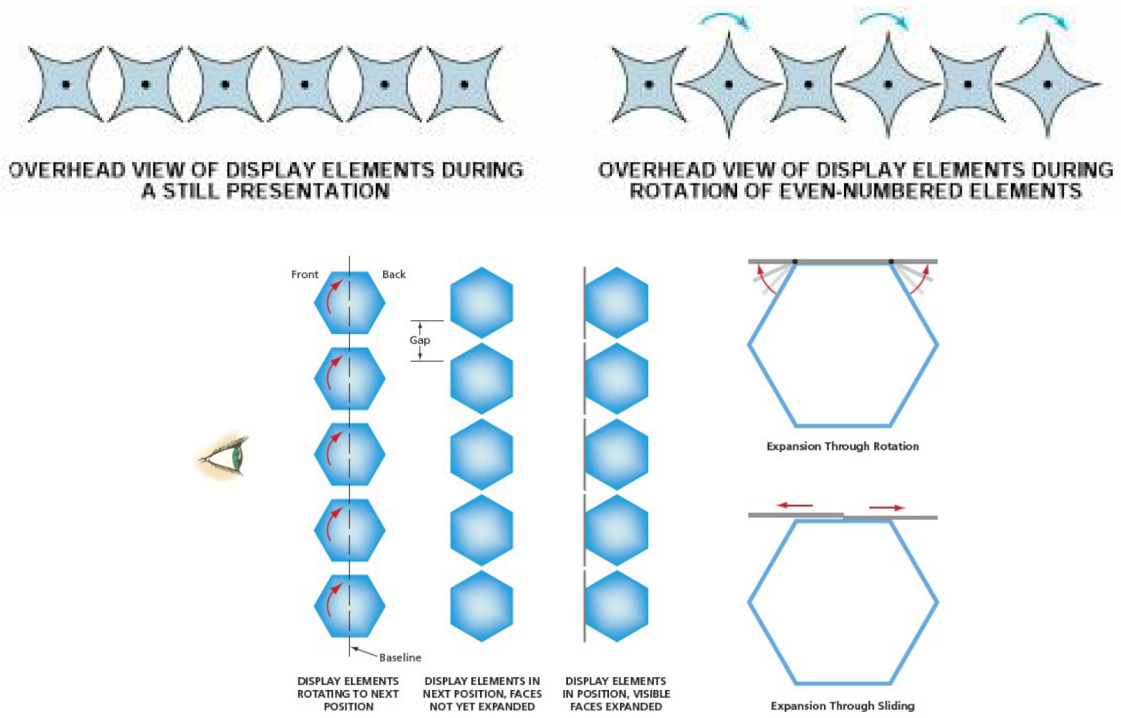


Figure 2.9: A proposal for four- and six-message electromechanical display systems (from [How07]).

2.4 Legal Situation

The following description of the legal conditions for installing a big outdoor display device is derived from the legislation in Vienna, Austria. The legal situation, however, is not always entirely clear and varies strongly from country to country. It even varies from province to province regarding the building code.

When installing a façade display in private or public areas there have to be considered a set of legal rules including both private and public law has to be considered. The rules of neighbourhood law from the civil code also has to be taken into account for neighbouring private and public parties. Besides these regulations also the building code is relevant. The civil rules of neighbourhood forbid therefore influences coming from the neighbouring plot of land if they imply disturbance through waste-water, smoke, gas, heat, smell, noise, vibration, light-emission and similar. Not only direct neighbours have the right to prohibit the construction of a disturbing element but also farther neighbours, if he/she is impaired by the structural changes [Kin06].

Further questions arise about the legal situation regarding traffic safety aspects. Visual displays carrying information which are not traffic related underlie certain restrictions and must follow the terms and conditions described in [Luk03]. Therefore the law forbids installations which might dazzle, disturb the free view, be confused with light signals – or reduce their effect. The guidelines and regulations from [Luk03] specify limits for light emissions and further – in case of reflections – the limit of the degree of reflection $\left(15 \cdot \frac{mcd}{lx \cdot m^2}\right)$.

The law differentiates also in terms of display content. The author categorises by smoothness, moving speed, refresh period, refresh time, blinking period, direction of movement and so on. Based on these categories the danger and the degree of distraction for road users is evaluated. The time of distraction for the driver should be one second maximum and the information on the display accordingly short and clear. Video walls are completely forbidden. The other categories of displays undergo a bureaucratic process and may be allowed or prohibited near streets.

Summarising the mentioned laws, a display device has to be accepted by neighbours and the legislation of traffic safety. It is more likely for the device to be legal if it is not dazzling, light-emitting, loud, blinking or disturbing by its transitions and motif-changing. The basic concept for the façade display device being developed in this work meets these properties and has therefore a certain advantage over several other concepts and products.

Chapter 3

Conceptual Framework

3.1 Basic Idea

The underlying idea is generally the most important key to come to a good end when developing something. Unlike buying a puzzle game where the goal, which has to be reached, is already pictured on the box, the main and most important challenge in development is to find the right idea and a way to realise it, which again is not even sure to be possible and what it might look like in the end. This chapter strives to show and comment this process of finding the best solution to a problem which has already been solved so many other ways. It is tough to solve it as described in Section 1.2, especially under the cost constraint.

3.1.1 The Driving Element

The Source of Physical Force

After the investigations made in Chapter 2 it was decided to use physical force in some way to show and hide the pixel's colour. This choice implies the need for a driving element. A closer look was given at these possibilities:

- Pneumatic system
- Rotary motor
- Linear motor
- Magnetic force

The idea to use air in a system of tubes to blow up some kind of balloon in order to make it appear and visible is a very nice one, but not feasible – it was soon dropped. A pneumatic system would also be expensive, loud, difficult to mount and complicated to control as it is not easy to switch it in a matrix.

Using electrical motors – be it linear or rotary – would be the most simple way to drive a pixel. The problem is, however, that such motors are too expensive: it can not be used a motor for every single pixel. Thus the goal is to find a way either to save resources in the driving element itself or in the number of driving elements. The approach to use expensive motors but fewer of them seems reasonable. It is possible to use one motor per row and one per column. This concept is developed in Section 3.3 and called from now on the *Mechanical Concept*.

The approach to use a cheap and simple engine per pixel leads to investigate magnetic fields and their effects. Magnets are tested on their applicability. Electrical magnets can be used to pull ferromagnetic material and they can be used to push an other magnet with opposite polarity. The second magnet can be an electric magnet or a permanent magnet. This basic idea is referred to as *Magnetic Concept* from now on and will be developed in detail in Chapter 3.2.

Power Transmission

In both scenarios (Magnetic and Mechanical Concept) the (electrical) power has to be transmitted to the driving element and from there to the pixel. The magnets need to be wired and wires can cause a high amount of cost, weight and need for space. But as the pixels anyway are installed in a matrix shape, it is evident to do matrix wiring. It does not only save a lot of meters of cable, but also the control circuit is cheaper, as every cable needs a switch as well.

For the Mechanical Concept it is also required to do matrix-like connections. Every engine corresponds to a whole row or column and the generated force must be transmitted to all the corresponding pixels. For instance this can be realised with

- a shaft,
- a connecting rod,
- a v-belt,

- a string or a cable.

The cognition made so far is the basis to be able to begin the development work. It was decided to develop two concepts. One approach shall use magnets – one per pixel – and the other one shall use a motor per row and one per column. As already mentioned it will be called Magnetic and Mechanical Concept during this work and the text will handle most of the developing process for the two rails separately.

3.1.2 General Mechanical Design Decisions

Pixel Unit

The pixels shall be solids showing one of their side faces to the observer. By turning the pixel a step forward, the exposed face changes and so does the colour at the front side of the display device. This concept is limited in number faces possible to be shown but due to its simplicity and robustness it is the preferable choice.

Points of Rest

The design must consider the claim that the pixel must remain in its state (orientation to the observer) also when the power supply is turned off. A mechanism must be provided for latching or even locking the pixel. It must be resistant to vibrations and wind. Figure 3.1 shows a possible solution for the issue.

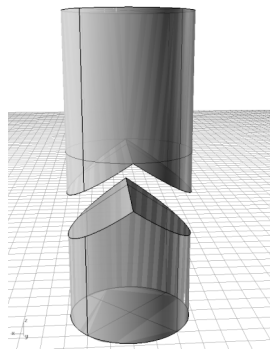


Figure 3.1: A latching mechanism to generate two points of rest at 0° and 180° revolution.

Axis of Rotation

Given the two possibilities to arrange the axis of rotation either vertically or horizontally in the display plane. The only difference between them is their orientation to the vector of gravitational acceleration. Gravity can have a fairly big impact on the behaviour of the moving elements and must thus be aligned wisely. At first gravity must not impede the desired movements and secondly it can be used to specifically create a certain effect in order to support the movement. For example the points of rest can be generated using gravity like in Figure 3.1. The reasons to decide in favour for the vertical axis are

- The axis does not get bent by its own nor the pixels weight
- Abrasion can be avoided in greater degrees
- The gravity can be used to take advantage of
- For every variation of a prism shaped pixel the cyclic movement is affected uniformly by gravity

The idea to combine horizontal and vertical rotating pixels in order to save space emerges, but this concept involves more problems than advantages.

Stable Pixel Orientation

The pixels are stable in orientation relative to the points of rest. The mechanism providing the points of rest itself must be stable in orientation to guarantee the pixels correct orientation. The pixels hanging construction must thus not turn but still allow the pixel to turn. Either the vertical axis provides it or a horizontal stabilization is added, which forms a stable grid.

Integrate the Mechanism Inside the Pixel

Every pixel has to be mounted separately among all the others in a way they do not affect each other but still provide

function. Within a quite small space all the functionality has to be squeezed in. The pixels should stick to each other without much space between them in order to avoid pixel borders. The space is thus very limited. Although the space behind the display could be used, the design goal was to put all the functionality inside the pixels. The benefit lies in the mounting of the device, which becomes much more simple and flexible. Furthermore the display can be eventually mounted to be seen from both sides.

Reduce Number of Moving Parts

Moving parts are the most critical part of the whole construction. Because of friction, abrasion and possible breach the model is increasingly valuable the less moving parts it consists of. It is obviously not possible to omit them but they should be minimized in number.

Simple and Effective Construction.

As the driving element had to be simplified and reduced due to cost reasons it is very tricky now – with these limited possibilities – to provide function and still find a design as durable as possible. Simplicity, meaning the usage of cheap parts and a straightforward assembly is the design goal which obviously leads directly to a robust model with low complexity. The mechanism needs to be innovative and also modular. Several pixels make up a module and tiling them must be simple without interference or gaps between them.

3.1.3 Pixel Shape

The pixel unit is meant to turn around its vertical axis in order to show a special side face to the viewer. The two main goals are a) to minimize the gap between two pixels and b) to maximize the amount of faces. As additional criteria the shape of the faces should also be considered: they should be flat because rounded faces affect the reflection characteristics, especially for different viewing angles.

The drafts in this section do not consider the additional gap that has to be added for physical tolerance reasons.

Two side faces can be put on a planar flag, but as the mechanism needs some space inside the pixel, it has to be designed in an elliptic shape like in Figure 3.2. With two side faces it is thus possible to omit any gap but the faces are slightly rounded.

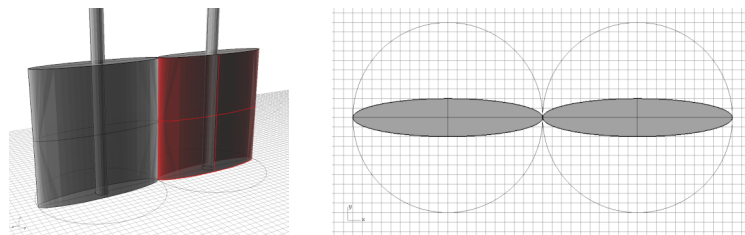


Figure 3.2: The proposed basis area shape for a pixel with two side faces.

Three side faces, the best trade-off. Three faces are not very much but the geometry is perfect to be placed side by side without gaps (Figure 3.3). In a lot of cases three side faces do the job and other solutions should be considered only if necessary. Besides, this shape is widely and effectively used for advertisement panels which interchange three messages.

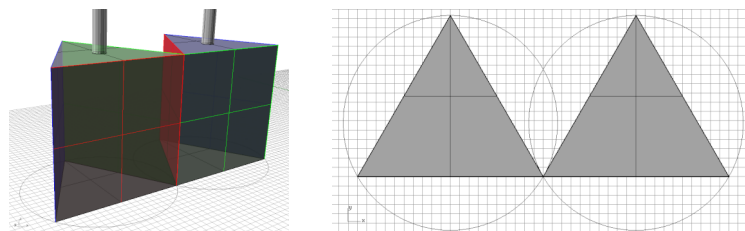


Figure 3.3: The proposed basis area shape for a pixel with three side faces.

Four side faces. To gain one more face, a significant drawback must be accepted. For example, just using cubes leads to a considerable large gap (Figure 3.4) and only one of two neighbouring pixels can be turned at the same time. The clue is, as already [How00] did, to incurve the side faces (Figure 3.5) to omit gaps. This heavily deforms the pixel and the reflecting characteristics may not be satisfying anymore. A compromise can be established by increasing the incurve radius and rounding the protruding edges. This way the gap grows but the faces become flatter.

These solutions may not meet everybody’s demands and another proposal has to be made. Thus, instead of deforming the cube, it is normally designed with additional flags on its edges (Figure 3.5, last image). The flags are thought to be either thin plastic flags easily bendable or they are fixed through a hinge and a return spring. The flags perfectly fill the gaps between the pixels and still allow turning. However, the model is not tested, thus the performance is questionable and these problems could occur somehow:

- Neighbouring pixels rasp each other
- The material could lose its flexibility due to environmental influences (→ use hinges)
- More effort is needed to turn the pixel
- The robustness is always affected by movable parts

This alternative design should be evaluated in future work.

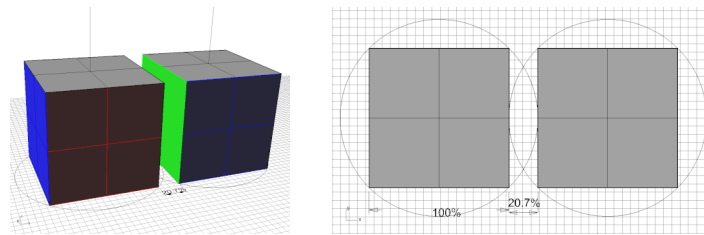


Figure 3.4: A four-sided pixel shape without adaptation leaves a big gap between two neighbours.

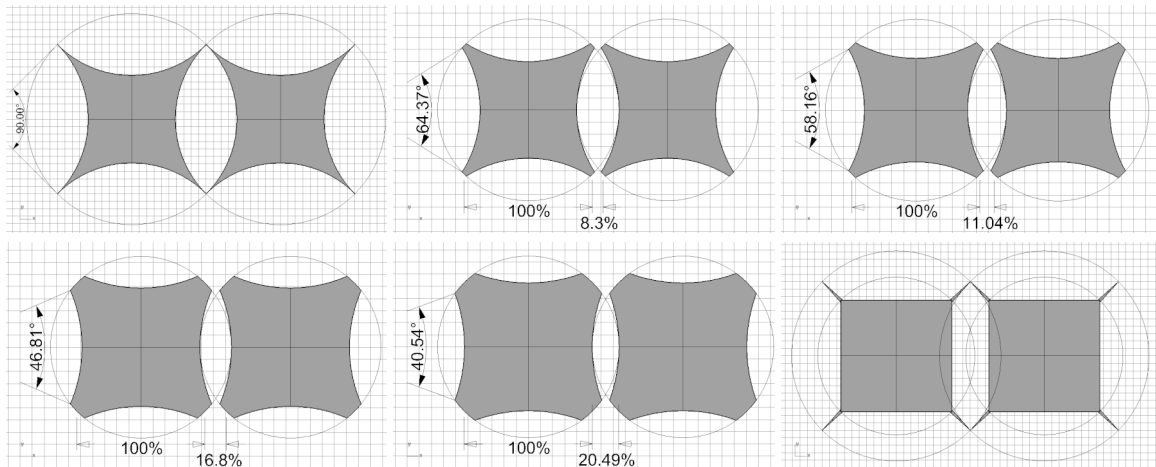


Figure 3.5: Different possible basis area shapes for a pixel with four side faces. First: No gap between pixels but heavily bended faces. Others: Increasingly incurving the side faces with a radius less than the pixels outer radius flattens the face but increases the gap distance. The percent values in the draft denote the length of the gap in relation to the width of the faces. The denoted angle is a measure for the degree of the face’s bending. Last drawing: A solution for four faces without gaps using deformable flags at the edges.

Five side faces. A prism with five faces is not applicable due to huge gaps. Additionally the angle between two faces in this case is only 60° which means that unwanted side faces are partially visible. An alternative solution would be to place a lense before every pixel in order to blow up the front side face of the prism and thereby omit the gap.

Six side faces The proposed construction in [How07] does not seem suitable. The prism reveals, however, an other possibility. Colouring the prism like in Figure 3.6 makes it possible to mix them. By showing two faces instead of one it is possible to mix colours. Rather than using two pixels to mix yellow, for instance, like this it is possible to mix it using only one pixel. The horizontal resolution of the image is doubled.

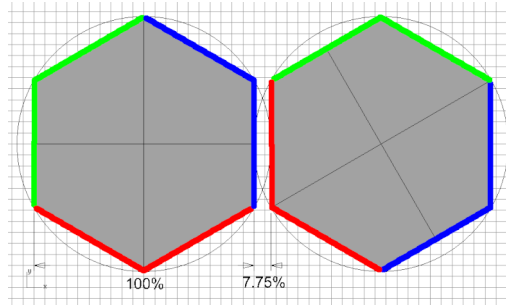


Figure 3.6: Six sides do not work the usual way but this shape reveals an other possibility.

More side faces. The mechanism proposed by [VRA05] (explained in Section 2.3) shall serve as basic idea. Its disadvantages, though, must be avoided. The driving belt is omitted and a vertical axis is introduced just like the other pixel designs have. Secondly, the coloured belt is not designed bendable, but rather foldable like a chain. Figure 3.7 shows a sketch with the desired properties and functionality. This model, however is only briefly tested and whether it works in an integrated system has to be proven in future work.

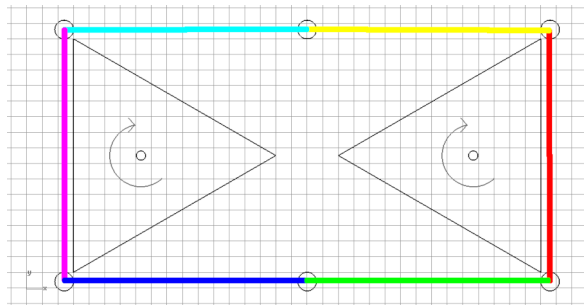


Figure 3.7: Proposed mechanism for an N-sided pixel: The plates in colour are connected like a chain and the triangular guide rolls turn them around in order to expose one after another to the viewer.

3.2 Magnetic Concept

3.2.1 Magnetic Field and Force

The used electromagnets are composed of a coil core and a wire wound around it. An electric current passing through the wire generates a magnetic field. The core is not necessary but a ferromagnetic material like iron is able to magnify the strength of the magnetic field.

Ferromagnetic materials have the characteristic of *remanence*. When magnetizing a ferromagnetic material, parts of the magnetic field remain also after removing the external magnetic field. The magnitude of remanence depends on the material and is taken from the hysteresis loop. The hysteresis loop can be measured with a B-H analyser [Wikb].

The only power dissipation in an electric magnet is the generation of heat. The heat itself is not a real problem in this case because the magnet is active for less than a second only. The heat, however, can be reduced by increasing the number of windings N and decreasing the current I . The power dissipation, $P = I^2 \cdot R$, increases with the square of the current and the magnetic field is proportional to $N \cdot I$. It is therefore possible, to create the same magnetic field with less power dissipation as long as the product of N and I stays the same.

3.2.2 Mechanism

After making the restriction to use only one magnet per pixel, a way has to be found to use this magnetic field in terms to mobilise the pixel. A short investigation in permanent magnets make clear that the costs for such material are too high to fulfil the desired goal (referring to [sup]). Besides, the intention is generally to spare every element which can be renounced. Evidently, the best way to turn the magnetic field into a directed force is to combine the neighbouring pixels in such a way, that they pull or push each other constructively. The sketch (Figure 3.8) shows how the magnets are arranged. Every single magnetic field can be poled in both directions and by reversing the polarity of one magnet, it senses repulsive force which leads to a rotation. There is no need to power the whole row of magnets. Two equally poled magnets are enough to turn a third contrarily poled magnet. The Magnetic Concept is limited to two pixel side faces due to the two poles of the magnet.

In some of the following designs a *mechanical end stop* is needed. Considering that the power supply cables may wind up if the pixel turns constantly the same direction, the magnet must instead turn alternatively clockwise and counter-clockwise. To achieve this behaviour, a mechanical end stop has to be established. The mechanical end stop implies also that the pixel may get stuck against it so the force produced by the magnetic field must be directed accurately.

The magnetic force drops with the distance, thus when a pixel has turned 90° , the distance is at its highest and the inertia at this point must be high enough to go beyond this critical state. The mechanism must be adapted to that problem and support the movement. For this reason the friction must be low.

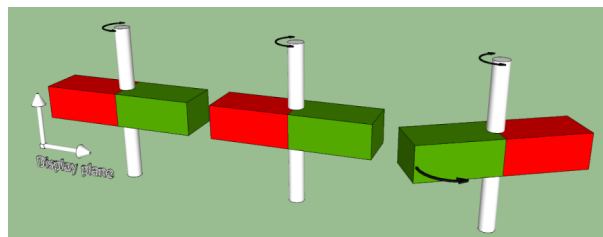


Figure 3.8: The magnets in a row interact and rotate by changing the polarities.

3.2.3 The Process of Design Refinement

The following sections describe the development from the basic idea to the final design. It only covers the planning while test results and will be presented later on. The practical realisation of the several designs and their final evaluation is handled in Section 4.1.1.

3.2.3.1 Mounting Through a shaft

This basic idea discussed in Section 3.2.2 in the first attempt leads to a simple construction (Figure 3.9). The coil core is designed to be drilled in order to be able to hang it on a shaft. The shaft is fixed in its orientation and a ring holds the magnet at its height. This ring is mitre-cut in order to give the pixel two stable points of rest as discussed in Section

3.1.2 (Figure 3.1). The cables are let loose. With this design it is important to use long cables with thin diameter and easily bendable material. Otherwise the cables could be a problem for the turning mechanism. To prevent the cables from winding up, a mechanical end stop is planned. An extra string shall be mounted on the frame. It shall serve as mechanical end stop for all the pixels in a column. This restricts the pixels from turning full 180° . The pixel's rotation is limited depending on the thickness of the string, the thickness of the electromagnet and its displacement from the pixel's centre of rotation. The distance from the centre influences also the radius r of the elliptical shaped pixel (cp. Figure 3.10). As not the whole 180° are possible to turn, the points of rest must be adapted as well. Refer to Section 4.1.1.1 for the realisation of the model.

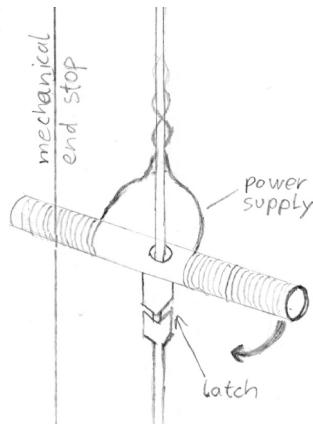


Figure 3.9: The sketch of the first design mounted on a shaft.

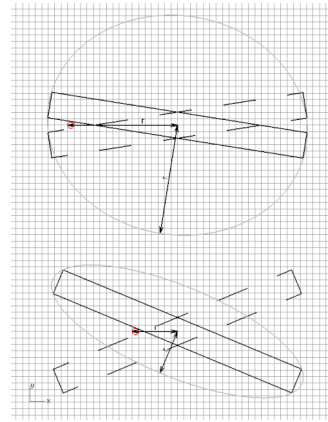


Figure 3.10: This sketch shows the impact of the mechanical end stop on the pixel cover's shape.

3.2.3.2 Sliding contacts

The purpose of this design is to replace the cable connection by sliding contacts in order to prevent the cables from winding up. By doing so, the mechanical end stop can be omitted (Figure 3.11). This model also reduces the friction by omitting the cables as well as the mitre-cut shaped hanging. As the pixel is now planned to be freely turnable without any limits or end stops, the points of rest can be established at exactly 180° and the magnetic force does not need to be directed in a certain direction. The rejecting magnets make the pixel to turn without fail. With this configuration the points of rest can be established by taking advantage of the remanent magnetism (explained in Section 3.2.1). The coil core remains magnetic and the direct contact to the neighbouring magnet should provide enough attracting force to make the magnet remain in its position. Although the design should work perfectly, while planning it has to be considered that the sliding contact is a very critical point of vulnerability and can be a decisive part in costs. Special materials have to be used and the whole mechanism must be isolated in order to avoid environmental influences that could distort the sliding contact's conductivity. Further evaluation is made after realisation in Section 4.1.1.2.

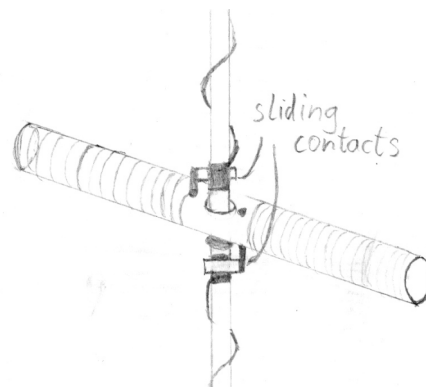


Figure 3.11: The sketch for the second prototype using sliding contacts.

3.2.3.3 Mounting Through Elastic Strings

The mounting has to be reconsidered as the presented solutions are not satisfactory yet. The shaft is not optimal in terms of friction and it is replaced by a string. The friction is way lower with the magnet mounted on a twistable string but in order to provide a bi-stable hanging, the magnet needs to be mounted at two points using more than one string. The conclusions made so far, the experiments and the cunning work led to a solution which meets the requirements. Figure 3.12 shows the principle attaching of the pixel using four elastic strings. They are mounted displaced in the frame in order to generate the two stable positions. Either the upper or the lower two strings are twisted by 180° and switching between these two states obviously turns the pixel. The principle of this design is very simple and promising. The applicability, however, is questionable because the pixel significantly changes its vertical position when turning, what makes the construction probably infeasible. The realisation and tests, as well as an evaluation are described in Section 4.1.1.3.

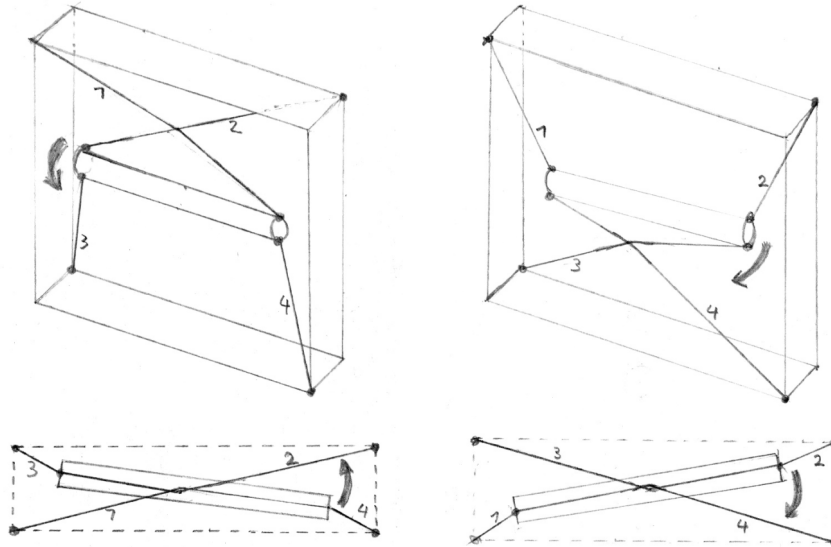


Figure 3.12: This design proposes a bi-stable hanging construction.

3.2.3.4 Mounting Through an Elliptic Hole

This design omits the direct connection to the magnet and is thus very similar to design 3.2.3.2; but also design 3.2.3.3 had a certain impact on the development. The magnet has an elliptic shaped hole in its middle and the stretched strings hold the magnet at its position and orientation. This way, the two desired points of rest are built-in and the strength of latching is easily tunable by adapting the elliptic radii. The string's strain must be tuned regarding the pixel unit's weight. The friction in this design is reduced to a minimum. The wiring is not completely solved but two variants are proposed. The first wiring variant again has two loose cables and implies thus the need of a mechanical end stop which prevents the cables from winding up. This mechanical end stop would look like the one in the design of Section 3.2.3.1, with all its trade-offs and disadvantages. The second wiring variant proposes to omit the cables and use sliding contacts like in design of Section 3.2.3.2. The two cables are then at the inside of the hole connected to the coil wires. As the magnet turns the contacts are interrupted and permuted which makes the controlling more complex but does not affect the functionality. The design still has some imperfectness:

- the behaviour is strongly dependent on the pixel's weight
- the strings must be stretched which is not easy to manage as there are more rows of pixels
- the mechanical end stop problem is unsolved
- the sliding contacts increase the error-proneness

None of both wiring options seem satisfactory but nonetheless the realisation is made and found in Section 4.1.1.4. After all, the basic idea with the elliptic shape is promising and therefore considered in further development.

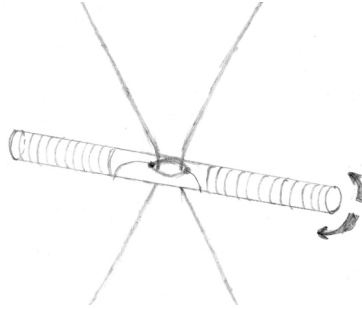


Figure 3.13: This design proposes an alternative low friction hanging.

3.2.3.5 Mounting on Cables with an Elliptic Check Rail

Based on the design in Section 3.2.3.4 this attempt combines the oval shaped hole and the simple hanging by two cables which are also meant to form the power supply (Figure 3.14). The oval check rail shall be fixed to the grid and serve as mechanical end stop as well as to provide the two points of rest. The deflection is not as bad as before but still not exactly 180° due to the mechanical end stop. The cables are stretched by the pixel unit's weight, so the deflection depends partially also on this. The positive side-effect of the deflection being less than 180° is that the magnetic force is automatically directed properly and the magnet does not get stuck turning in the wrong direction. The check rail is planned to be mounted to the grid with fixed orientation. The grid itself is made of cables and shall serve as power supply and supporting element in one. The vertical grid connections carry the weight and the horizontal ones accomplish the pixels orientation and horizontal alignment. The realisation of this model is described in detail in Section 4.1.1.5 and it is ultimately chosen to be the final solution.

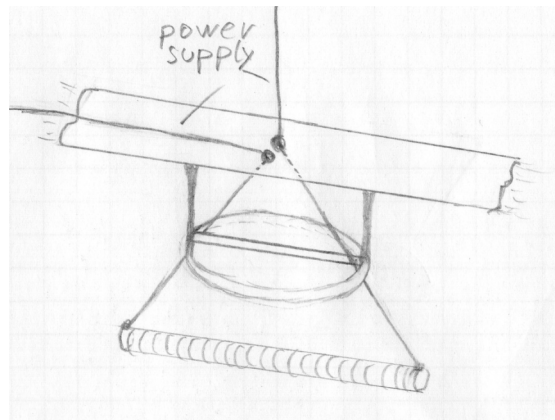


Figure 3.14: The final design for the Magnetic Concept.

3.2.4 Driver Circuit

The driver circuit is the electrical circuit needed to power and control the magnets. The electrical switches must be accurate in timing and able to bear high currents. For different display device and pixel sizes the circuit must be adapted to the actual needs.

The coil cores are 80 mm long and 5 mm in diameter. The enamelled copper wire used for the coil is 0.07 mm^2 (0.3 mm^2 with isolation) thick and 7 m long per magnet. The wire's resistance is calculated by

$$R [\Omega] = \frac{\rho \left[\frac{\Omega \cdot \text{mm}^2}{\text{m}} \right] \cdot l [\text{m}]}{A [\text{mm}^2]} = \frac{0.01678 \cdot 7}{0.07069} = 1.661 [\Omega]$$

ρ is the resistivity, in this case for copper. The resistance of the load to drive is thus 1.66Ω . Defining the power supply voltage to $12 V$ and applying Ohm's law $U = R \cdot I$ the resulting current is

$$I [A] = \frac{U [V]}{R [\Omega]} = \frac{12}{1.66} = 7.22 [A]$$

Seven ampere is a fairly high amount of current, but by changing the coil configuration referring to the formulae in Section 3.2.1, it can be adapted as desired.

Figure 3.15 shows how the magnets are connected. The rows are switched between $0 V$ (ground) and n.c. (not connected, high-resistance) and the columns are switched between n.c., $-12 V$ and $+12 V$. In this grid it is possible to switch several magnets in a row with different polarity at the same time.

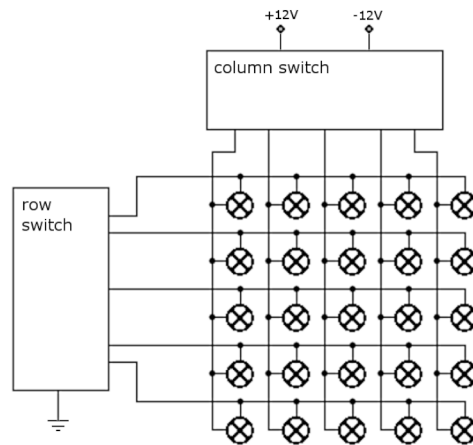


Figure 3.15: The magnets are placed in a grid and wired in a matrix.

The circuit for the power supply is shown in Figure 3.16. It provides the symmetric positive and negative 12 volt for the electromagnets and a separated power supply for the gate driver and microprocessor. Two separated power supplies are used because the coils produce distortions which could harm the ICs. The suppressor diodes are additional safety measures as well. In order to switch big loads the best choice is to use metal-oxide-semiconductor field-effect transistors

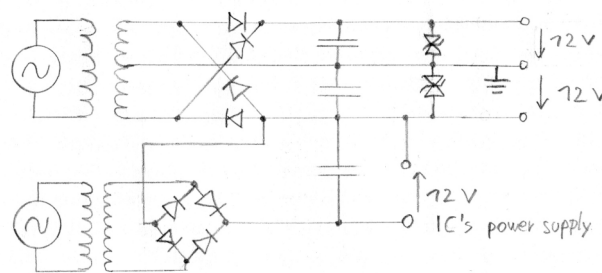


Figure 3.16: The power supply circuit.

(MOSFETs). A MOSFET is a voltage driven device and is itself operated through a gate driver which charges a high voltage needed to activate the transistor. The charging is done through a bootstrap capacitor. The gate driver used is the FAN7380 [Cor05]. Figure 3.17 shows the circuit which is used to switch the columns. The row's connections are the common drains for all the loads in a row. A row switch must thus be dimensioned to bear the sum of the currents of simultaneous active magnets. Using MOSFETs in this case leads to a more complicated circuit because one and the same switch must support current flow in both directions. The problem can be solved by using a rectifier (Figure 3.18). An alternative very simple solution is to use a relay or a solid state relay. Finally, however, the best compromise in terms of cost and functionality is to use a Triode for Alternating Current (TRIAC). TRIACs can switch alternating current through an either positive or negative control pulse. The TRIAC switches then to low-resistance and remains in this state until the current flow ceases.

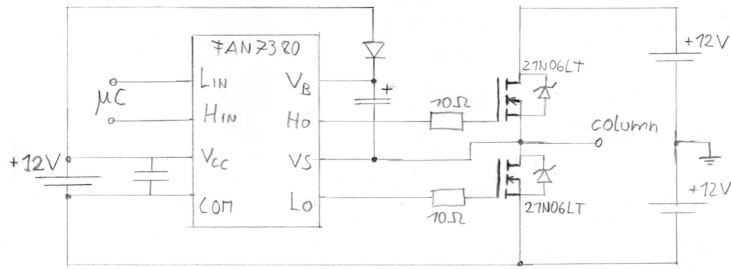


Figure 3.17: The circuit to switch the column connections.

The circuit is thus straight forward (Figure 3.19) and also easy to control. Instead of using an expensive high power TRIAC, as well cheap low power TRIACs can be used, connected in parallel.

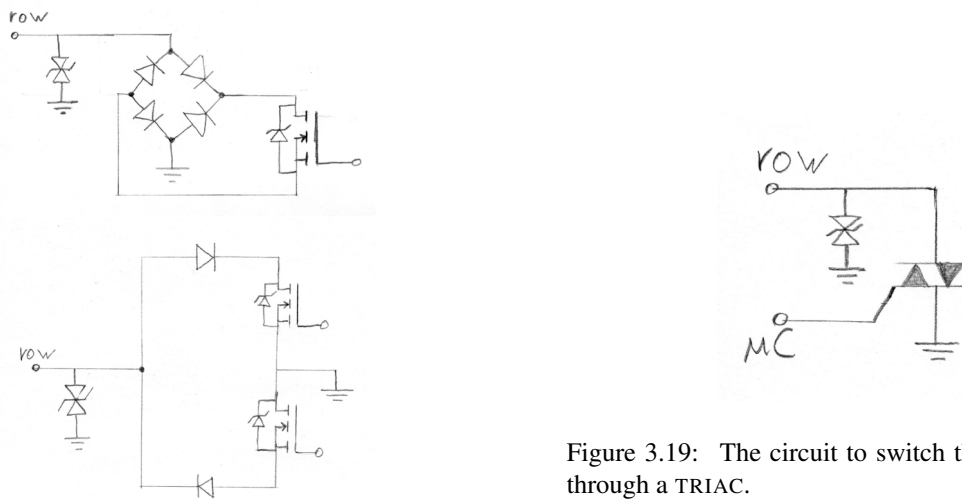


Figure 3.19: The circuit to switch the row connections through a TRIAC.

Figure 3.18: Two alternative circuits to switch the row connections through MOSFETS.

3.2.5 Controller

Every row has two (gnd, n.c.) and every column has three (-12V, +12V, n.c.) states. Assuming a display module consists of 8x8 pixels, the rows make up $2^8 = 256$ states and need a digital wire per row. As always only one row is active in praxis there are only 8 states and therefore only $\log_2(8) = 3$ wires needed. The columns with $3^8 = 6561$ states – if encoded – require $\lceil \log_2(6561) \rceil = 13$ wires. The encoding could even be optimized considering that always only five neighbouring magnets are active simultaneously. Encoding is easy to implement at the software side, but requires additional logic for decoding at the hardware side. Thus, it is not recommended to encode the columns unless the micro-controller has too few I/O ports. The most simple solution is to use two cables per column and to have an unused state per column. The used micro-controller is the ATmega328 [Cor09]. It is connected to a pc using a USB connection.

3.3 Mechanical Concept

3.3.1 Mechanism

"Mechanical Concept" means the idea of using driving elements not for every single pixel, but only one per row and one per column. This implies that a more expensive motor can be used but the force has to be transmitted mechanically to the pixels. Every pixel unit is thus connected to two forces, the motor of its row and the motor of its column. The pixel must not be affected when only one motor is active. Only when both its column and row are activated, the pixel unit has to turn these forces into a rotational movement in order to change the pixel's side face. Unlike in the former design, where the magnet with its two poles restricts the number of side faces, it is now possible to arrange more pixel side faces and adapt the turning mechanism freely. To transform two either linear or rotary forces into one rotary force is the main problem and a simple and robust functionality with finesse is needed.

3.3.2 The Process of Design Refinement

for a better understanding the following sections are divided into modes of driving and describe the planning of the prototypes. Again, the evaluation made here is only theoretical and is completed after realisation in Section 4.2.1.

3.3.2.1 Driving Through a Rotary Shaft

The rotary column motor drives the vertical axis and the linear row motor activates the mechanism. The pixel is hung on (but not joined to) the rotary axis. In the non-activated state the pixel is ought to keep its orientation, thus a locking mechanism is needed. Locking means that the pixel keeps its orientation relative to the grid even when the vertical axis turns. Only when the row motor activates the pixel, the lock is deactivated and the pixel is joined to the turning axis in order to let the pixel rotate by a specified angle. The join must be reliable and must not depend on friction only. The mechanism sketched in Figure 3.20 shows the functionality bent open for better understanding. The violet part is fixed to the horizontal grid, the green one forms the vertical rotational axis and the cyan part is the actual pixel. The horizontal rod, which does the lifting of the pixel (red) in order to activate it, is not depicted in this sketch.

Based on this mechanism a possible design is shown in Figure 3.21. It has a latch with the same principle as described in Section 3.1.2. The horizontal rod manages the orientation of the pixel unit and is able to lift the pixel in order to unlock it and to join it to the gear of the vertical rotary axis. The vertical axis then – through the gear – turns the pixel by the desired angle.

The rotation angle depends on rotation time and rotation speed ($\alpha[^\circ] = a[^\circ/s] \cdot t[s]$). To accomplish an accurate turn either the rotation speed is set constant and the row motor triggers the pixel accurately by means of time, or the column motor is accurate enough to turn the previously activated pixel by a specific angle. The latter solution is slower than the first one because the column motor has to accelerate and decelerate. Depending on the used hardware, the timing of the movement can be difficult to fulfil.

During activation the pixel moves vertically, thus a vertical gap between the rows of pixels is necessary. Also the horizontal rod may be a weak point in terms of robustness. The evaluation of the corresponding prototype is found in Section 4.2.1.1.

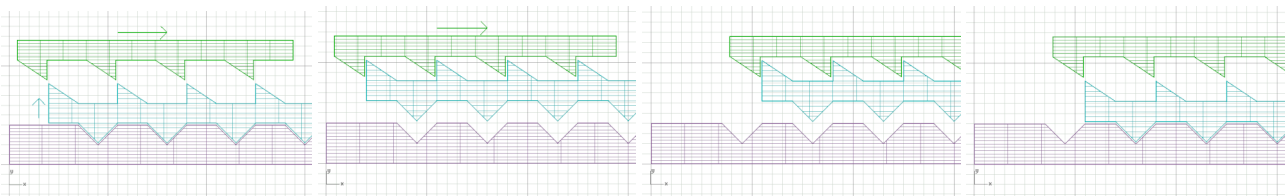


Figure 3.20: The sketch of the bent open mechanism. It provides function to turn the pixel with a rotary force.

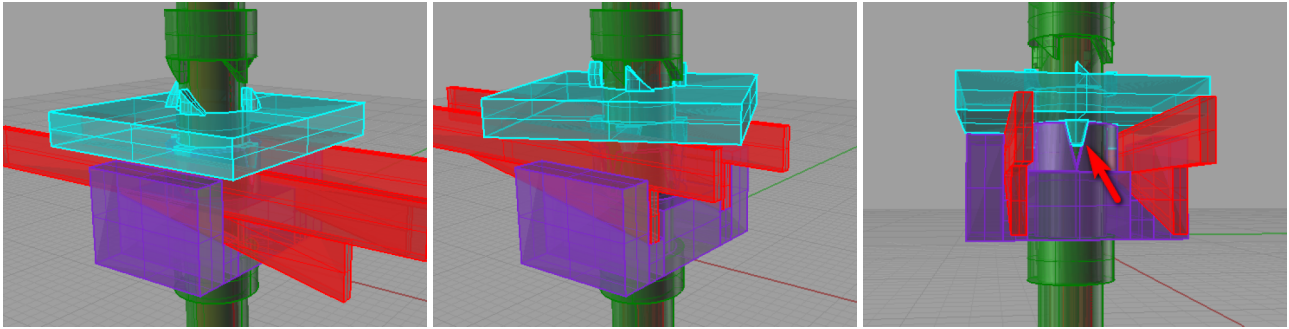


Figure 3.21: This design uses linear and rotary forces. The pixel unit is not activated in the image on the left. The middle image shows the activation by the red. The arrow in the image on the right indicates the locking mechanism. While the pixel unit is locked, the green axis can keep rotating.

3.3.2.2 Driving Through Linear Force

The pixel is planned to have a mechanism built-in converting linear movement into a rotary one. When both the row and the column motor are activated, the pixel shall turn one step around (a step is generally 120° for three side faces, but can vary). The conversion of the force is made possible through a sophisticated mechanism derived from the functionality of a ball-pen. Figure 3.22 shows the mechanism bent open. The blue part is fixed and is called *hanging*. The violet part in the sketch is the *turner* and represents the actual pixel with its side faces. The red part is called *trigger*. Pushing the trigger upwards leads the turner to unlock and to do a shift to the next tooth of the hanging. Like this by only using a linear force and gravity the turner rotates. The turner is prevented from turning, unless the trigger is lifted. Figure 3.23 shows the same principle as it is planned to be realised in Section 4.2.1.2.

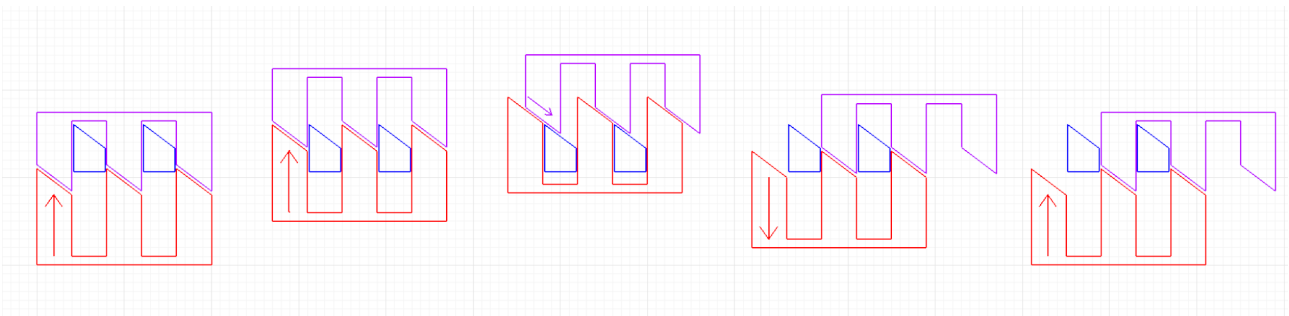


Figure 3.22: The sketch of the bent open mechanism. It provides function to turn the pixel with a linear force.

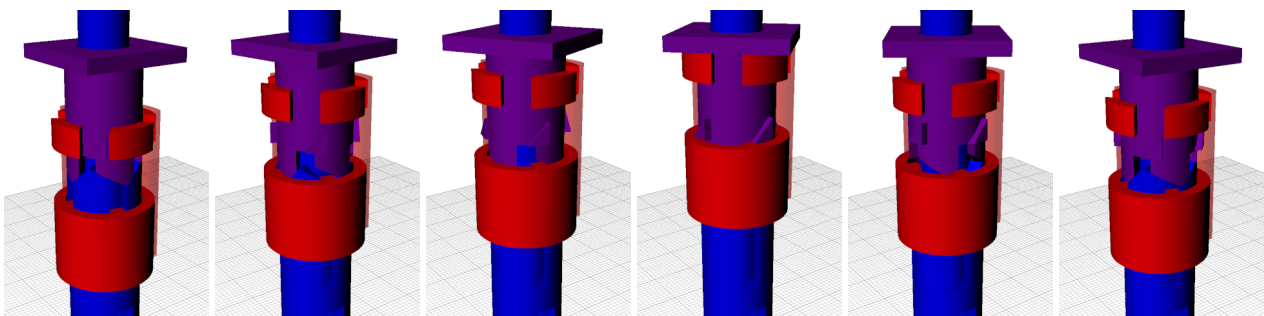


Figure 3.23: This model shows the mechanism functionality. Lifting the trigger causes the turner to move on turning to the next tooth of the hanging. Like this it is possible to turn the pixel with a linear force only.

Activation and Driving I

The presented mechanism must be activated and driven by the two linear motors in the column and row. This activating mechanism design proposes to accomplish the vertical movement of the trigger by elevating a horizontal rod and lowering the vertical axis. Figure 3.24 shows how the horizontal rod pushes the trigger halfway up and how the blue vertical axis is lowered in order to fulfil the movement. This leads to a turn as shown before. If only the column or only the row are activated, the pixel does not turn.

Activation and Driving II

The pixel is activated by its row motor and uses the column motor's force to turn. The mechanism implies some improvements in performance to the previous activating mechanism. In this design (Figure 3.25) the row motor is not meant to lift the trigger, but to activate a mechanism in order to allow the column motor to lift the trigger. If the row is not activated, the trigger is just not affected by the column motor. This way the mechanism is more robust and reliable and the row motor can be designed with less power. There is also no more need to move the vertical axis. The axis is drilled instead and a wire in its middle transmits the force to all the pixels in the column.

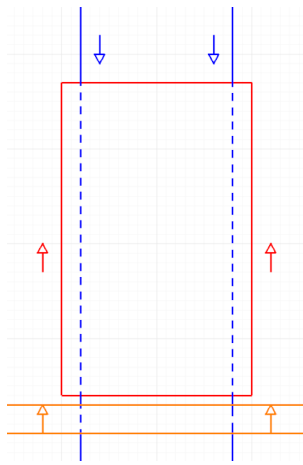


Figure 3.24: The first proposed activation/driving mechanism. The horizontal rod lifts the trigger (red) halfway and by lowering the vertical axis (blue), the activation is fulfilled.

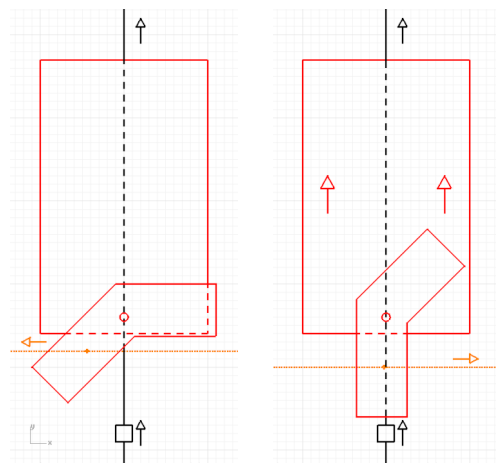


Figure 3.25: The second proposed activation/driving mechanism. The vertical string is only able to lift the trigger, if the horizontal motor activates the mechanism.

Both designs, however, are ideas which only explain the planning of the basic principle. During the planning it is not easy to foresee the complications of building such a prototype. The designs work perfectly in theory on the paper, but have to be proven later on by testing the functionality. Section 4.2 describes this process of construction, testing and refinement. It therefore implies further changes. Changes have to be made in order to improve the applicability and function. The drawing presented, however, is the essence of the final mechanism and represents the basic idea developed on paper.

Chapter 4

Realisation

4.1 Magnetic Concept

4.1.1 Realisation of the Designs

4.1.1.1 Mounting through a shaft

The prototype, according to the design presented in Section 3.2.3.1, is built in order to be able to test its functionality and performance. Its construction (Figure 4.1) is easy and straight forward. The magnet is mounted on a vertical shaft and the power supply cables are let loose. The unattached cables must not prevent the magnet from turning, so they have to be very elastic and thin but still isolated and thick enough to bear the high current. The configuration turns normally when powering the electro magnet with a DC voltage of 12 Volts (all the tests use 12 Volt). The resulting current is around 7 Ampere. The power supply cables and the mitre-cut rings reveal to cause more friction than the magnetic force can bear. When some weight is added in order to simulate the mechanism under more realistic conditions, this construction is problematic in terms of friction and the magnetic force is not strong enough to trigger a full turn by 180° . Tuning the mitre-cut sharpness, i.e. decreasing the inclination, decreases the friction but the latch becomes less reliable or even not functional. Finally all these attempts failed or could not sufficiently improve the performance:

- The inclination of the mitre-cut tube was changed
- The plastic tube was exchanged with a metallic one
- The radius and thickness of the ring was decreased
- The cables were interchanged by several others with different thickness and isolation material

For this coil configuration it is not possible to enhance the magnetic field. The configuration could be changed by either decreasing the pixel's size (coil length), raising the voltage or adapting the coil's windings and current. These changes, however, can not be made due to previously made restrictions.

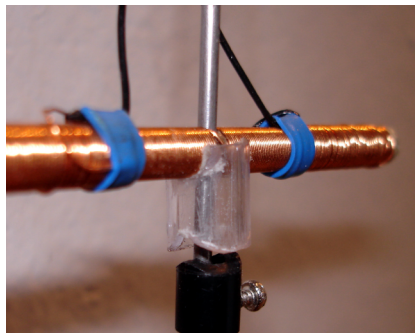


Figure 4.1: This construction is hung on a shaft and has a mitre-cut latch.

4.1.1.2 Sliding contacts

The design from Section 3.2.3.2 strives to reduce the friction and to omit the problems with the points of rest. By omitting the loose cables and replacing them with sliding contacts some problems disappear. Without loose cables there is no need

for a mechanical end stop and the points of rest can be established by remanent magnetism, as already described. Getting rid of the cables also means a certain decrease of friction. The shaft forms the first and the metallic ring the second conductor (Figure 4.2). Yet all these advantages can not cancel the side-effects this constructions involves:

- A sliding contact requires maintenance which has to be avoided
- Since the device should also work outdoors it would definitely have to be isolated
- The materials for a sliding contact, like carbon, are expensive
- Using cheaper materials than carbon leads to contact faults

Due to these drawbacks the concept is infeasible, although the prototype has fairly good performance. The overall good results of the tests with this prototype are only reduced by occasionally occurring contact faults due to not optimal chosen materials. The contact faults mostly cause a malfunction irreparable without human intervention.

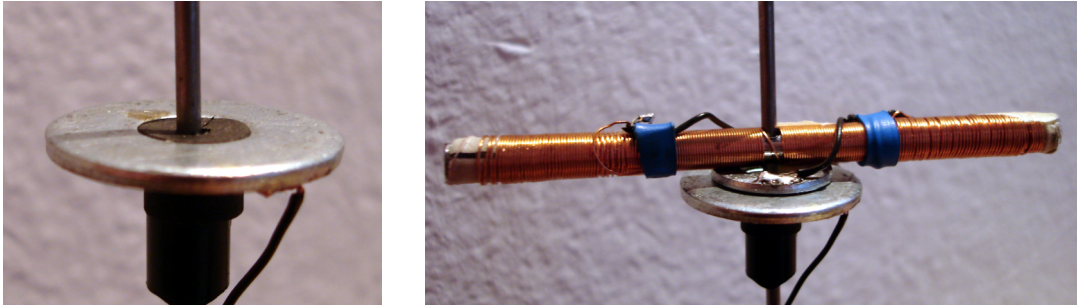


Figure 4.2: This construction solves some problems through sliding contacts.

4.1.1.3 Mounting Through Elastic Strings

As proposed in Section 3.2.3.3 this design introduces a new hanging concept. The pixel is fixed at four elastic strings which are displaced mounted in the frame. The diagonal displacement and a twist provide two stable points of rest. The simple principle works perfectly under certain circumstances, but some objections emerge: The vertical displacement between the two states is not avoidable. The rotation even exceeds the 180° which makes it complicated to direct the magnetic force between two neighbouring pixels. The tests on this single pixel are difficult to arrange because the stiffness of the strings has to be accurately tuned. This fact makes it even more complicated when trying to arrange more pixels. Finally the concept is evaluated as not feasible but the gained knowledge contributes to the following designs.

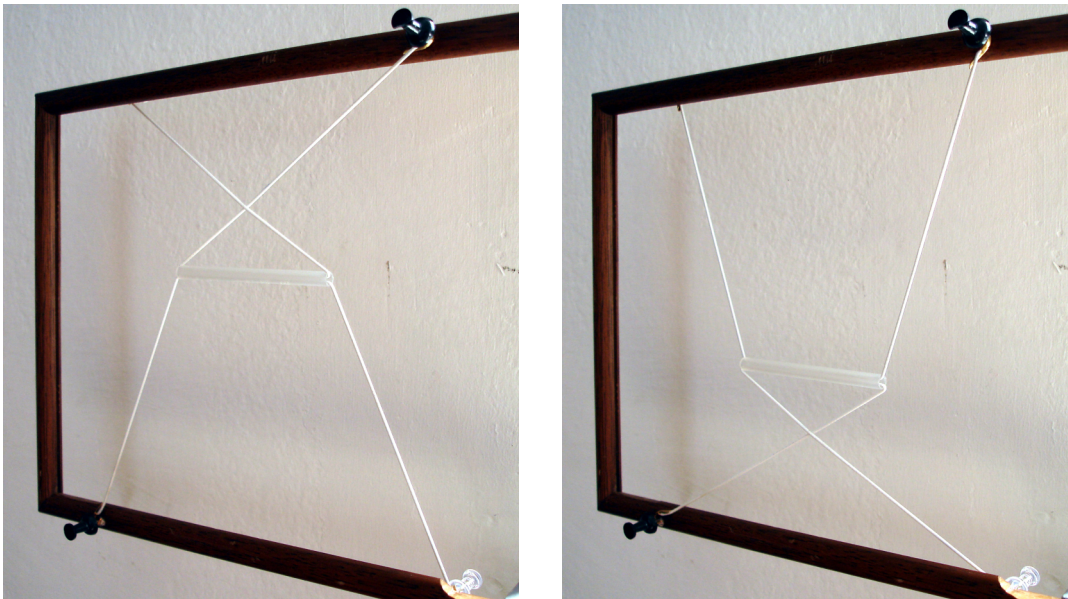


Figure 4.3: This bi-stable hanging mechanism minimizes the friction.

4.1.1.4 Mounted through an Elliptic Hole

Figure 4.4 shows the realisation of the design from Section 3.2.3.4 without strings connected to the magnet. When stretched, they still hold the magnet. This construction almost has no friction and the points of rest are built-in. The elliptic shaped hole in the magnet guarantees the desired orientation of the pixel when the strings are tight. The wiring is again done normally using two loose cables. The solution works perfectly but there arise some obstacles:

- the behaviour is strongly dependent on the pixel's weight
- it is not easy to stretch the strings accurately, as there are more rows of pixels

Although in the testing circumstances the function is very good, the design is not applicable also because it implies either loose cables or sliding contacts which have already been evaluated as not feasible. Still this model is the decisive one leading to the final solution.

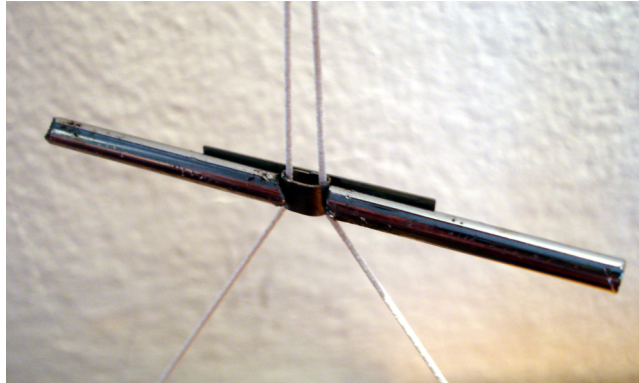


Figure 4.4: This construction has low friction and better performance than the former one from Figure 4.1.

4.1.1.5 Mounted on Cables with an Elliptic Check Rail

This design (proposed in Section 3.2.3.5) evolved from all the previously gained knowledge and is somehow a combination of all the previous research and tests. The construction of this prototype, however, turns out to be more difficult than the previous ones. The pictures 4.5 show some of the failed attempts to build the hanging construction with differently shaped and partially flexible check rails. Finally an easy way of assembling is found (Figure 4.6). It consists of an easy-to-produce metal sheet and four plastic strings. The magnet is drilled again and it is like this attached to the grid which gives more stability to the hanging and the movement. Figure 4.7 shows the fabrication of the main part. The construction is working robustly and a series of pixels is built arranged in a grid. The tests deliver satisfying results.

At this point of development by chance there was the opportunity to print the whole model on a 3D printer. With this great possibility some details have to be changed and some can be improved. The previous limits disappear and with the use of a CAD tool and GML software it is now possible to model and print an optimised construction (Figure 4.9). The hanging construction is now a single part and with the big accuracy of fabrication the performance is even better. The mechanism and behaviour is the same as before. The check rail is now in a perfect elliptic shape and the cable attachment is placed more centric, closer to the vertical axis in order to ease the rotation. The check rail is divided lengthwise in its middle, forming the end stop.

Figure 4.10 shows the proposed pixel cover. It is cut out from a thin plastic sheet and bended around the magnet.

4.1.2 Operation

Not powered neighbouring magnets occasionally interfere the functionality. When using two magnets to turn the third, eventually the third magnet attracts its other neighbour (which is turned off but still ferromagnetic) and can thus not turn. Although it is not a constant problem and arises only in certain circumstances the mechanism has to be changed. Instead of two magnets, four are used. Two to the left and two to the right of the pixel to turn. Like this the movement is more stable and even more force is available. Due to this change the pixels at the end in a row can not be handled the same way as the rest. Thus fixed magnets are added at both sides at the end of each row to solve both these problems. Furthermore this intervention makes it easier the calibration from a random state.

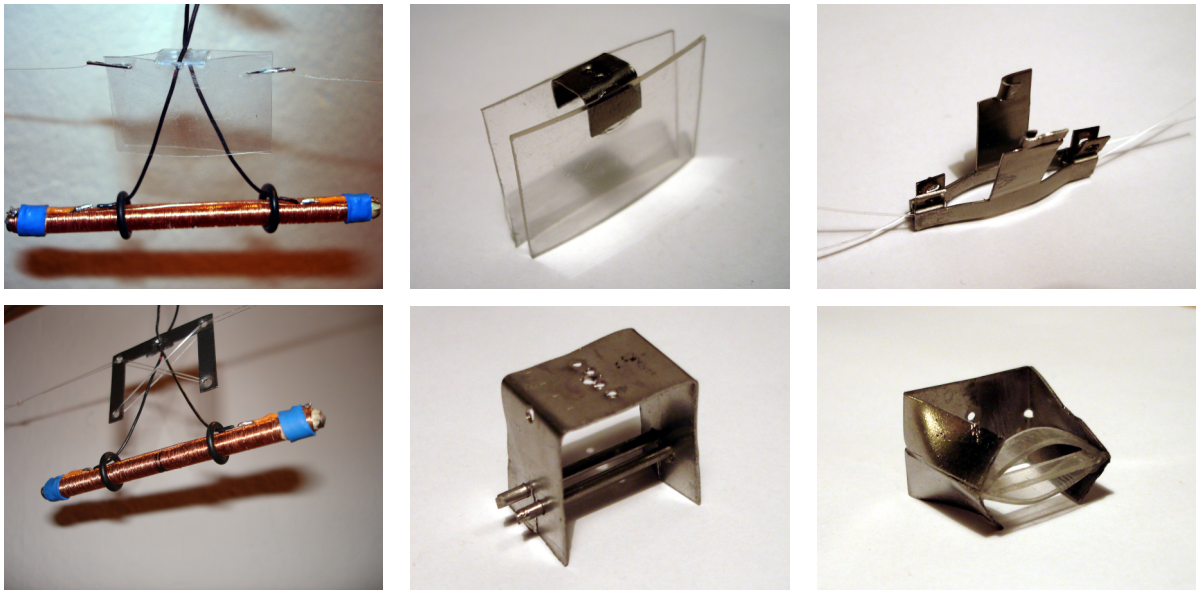


Figure 4.5: These are attempts to build the hanging construction. Different materials and shapes have been tested.

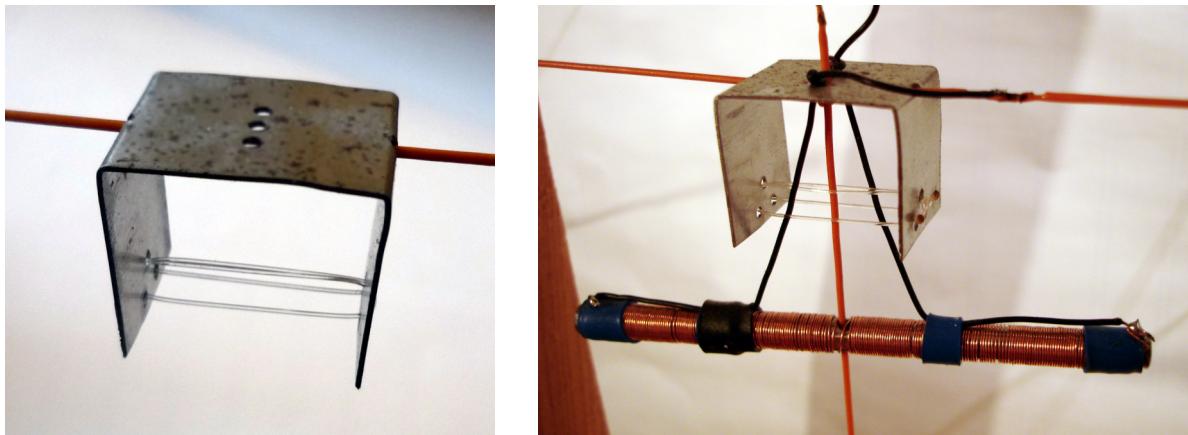


Figure 4.6: The final construction meets all the requirements.

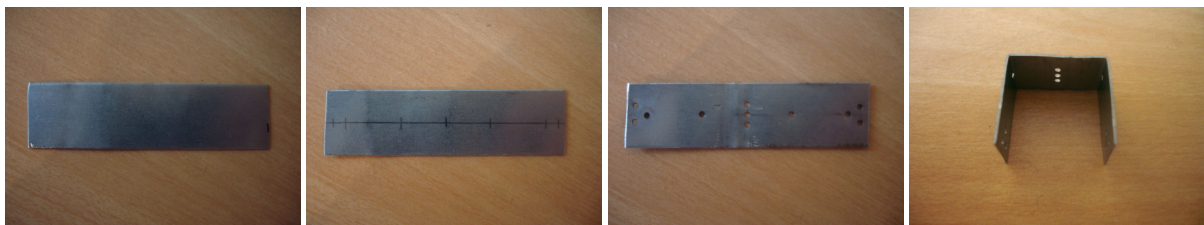


Figure 4.7: The fabrication of the hanging.



Figure 4.8: With a 3D printer it is possible to easily test several models.

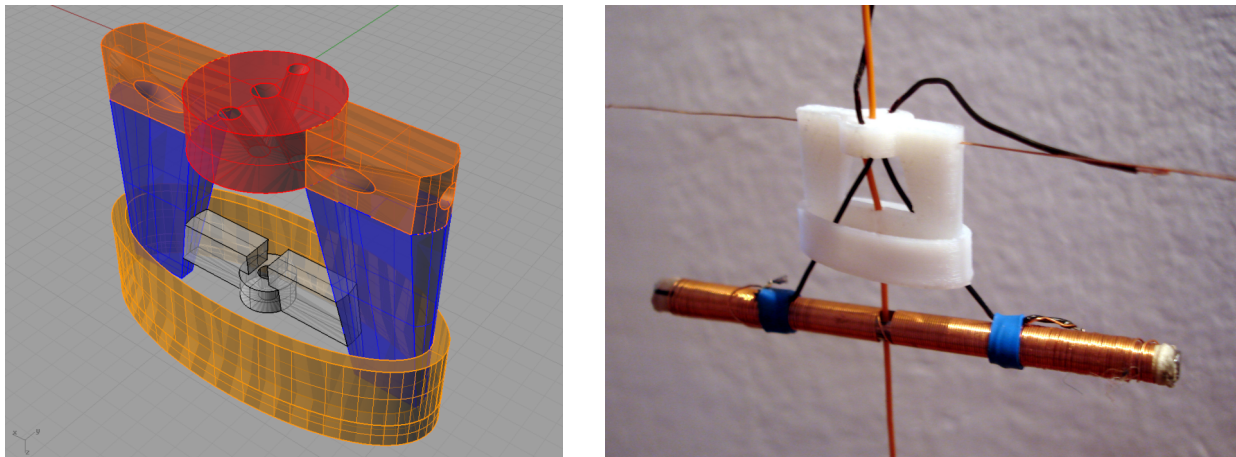


Figure 4.9: Printed in 3D the construction is optimised without limits in fabrication.

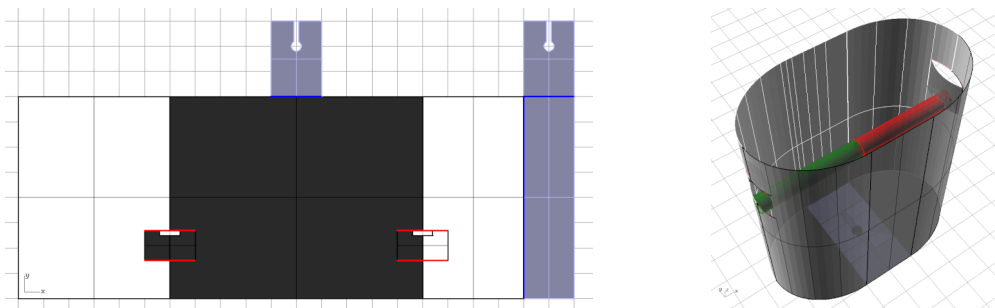


Figure 4.10: The pixel cover is made of plastic. The red lines are cut and the blue ones are folded. Bending it around the magnet results in the desired pixel shape and stable fixation.

4.2 Mechanical Concept

4.2.1 Realisation of the Designs

4.2.1.1 Driving Through a Rotary Shaft

The design developed in Section 3.3.2.1, realised as a prototype, does not show the presumed performance in the tests. The Prototype (see Figure 4.11) is designed for six pixel side faces and is in total 5x5 cm in size. The 3D printout of the digital model is generally working, but not as expected. However, basic tests allow making the conclusion that the design is not the preferable one. The reasons for this decision are:

- the controlling and triggering of the mechanism is either very slow or not accurate enough
- the design requires more accurate fabrication than possible in the course of this work
- the horizontal activator is confronted with more friction than estimated

The principle of lifting the turner (best seen in Figure 3.21 also implies complications. The trigger is in direct contact while pushing the turner and causes friction. In this prototype the friction is too high and the behaviour is occasionally affected. At times the turner even got stuck and therefore robust operation can not be provided by this design. Also, as already mentioned before, the motors must be controlled accurately in order to ensure robust triggering of the mechanism. Accurate triggering can be a problem because the force is transmitted mechanically from the motor to all the pixels in a row or column. Mechanical force transmission is not precise enough for this matter.

4.2.1.2 Driving Through Linear Force

Activation and Driving I

The design developed in Section 3.3.2.2 is printed out based on the digital models. Figure 4.12 shows the first 3D printout, again with six pixel side faces. As planned, the trigger is lifted by a horizontal rod, lying in the check rail (left photo). The vertical axis can then be lowered in order to actually turn the pixel (middle photo). The construction itself is robust and easy to fabricate and assemble (right photo), but the tests show that this activating solution (Activation and Driving I in Section 3.3.2.2) is not feasible when more pixels are cascaded. The arguments clearly argue against this method of activation:

- The horizontal rod initiating the lifting of the trigger is not realisable strong and small enough to be able to activate the whole row. With increasing numbers of columns, the total weight of the pixel units and the length of the rod become too high.
- Secondly the vertical axis has to be lowered in order to fully trigger the mechanism. As the vertical axis gives most of the stability to the construction, it is preferable not to make it a moving part. It may also affect other pixels by doing so.
- With this design it is not possible to make the whole construction flexible in order to adapt to structural irregularities. The vertical axis needs to be solid and strong in order to prevent folding. This demand implies a lot of unnecessary weight.

In fact, the horizontal and vertical rods should by no means be used as skeletal structure and linear actuators at the same time. Furthermore it is highly preferable to use something flexible for the vertical grid connections. A spring wire for example would do a great job. As it is not possible to implement it with this design it shall be considered in the second option.

Activation and Driving II

The second proposed activation mechanism (Activation and Driving II in Section 3.3.2.2), realised in the prototype in Figure 4.13, shows overall good test results. The model consists of three parts (left photo) and is designed for four pixel side faces in this case. The activation mechanism is solved through a sophisticated constellation of a metal part with a weight. This activation mechanism is designed to be defaultly deactivated by its own weight. The pixels in a column are all connected through a string to their column motor. The string is inside the vertical axis and it can be seen marked red in the middle photo. In the non activated state (middle photo) the linear motor does not have any effect on the trigger. The linear row motor can cause the mechanism to activate the pixel (right photo). In this state the column motor effectively triggers the pixel to turn. The linear force is directly transmitted to the trigger which unlocks and turns the pixel. This prototype is activated by a horizontal linear force and driven by a vertical linear force.

The operation is as simple as reliable. The described mechanism is robust in function (largely used in most ball-pens) and cheap in production. Unlike a pen, this construction does not need a spring for resetting the turner. It uses gravity. The metal parts of this prototype will later on be replaced with plastic ones. These are lubricated once at installation and due to not very high weight, the abrasion is also not expected to be a problem.



Figure 4.11: This prototype with a rotary shaft shows has not a satisfactory performance.

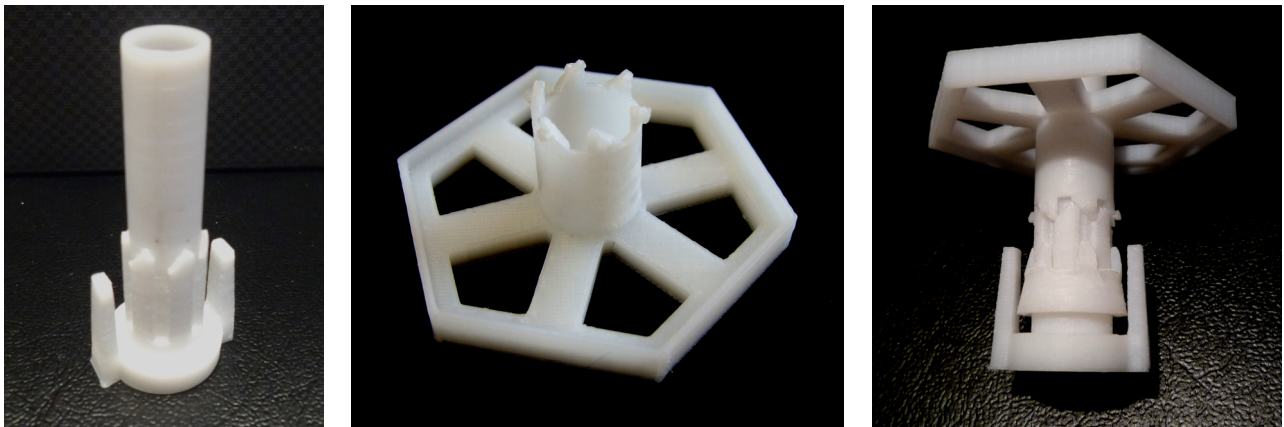


Figure 4.12: This prototype uses the sophisticated ball-pen mechanism which performs well. The activation mechanism still needs improvement.

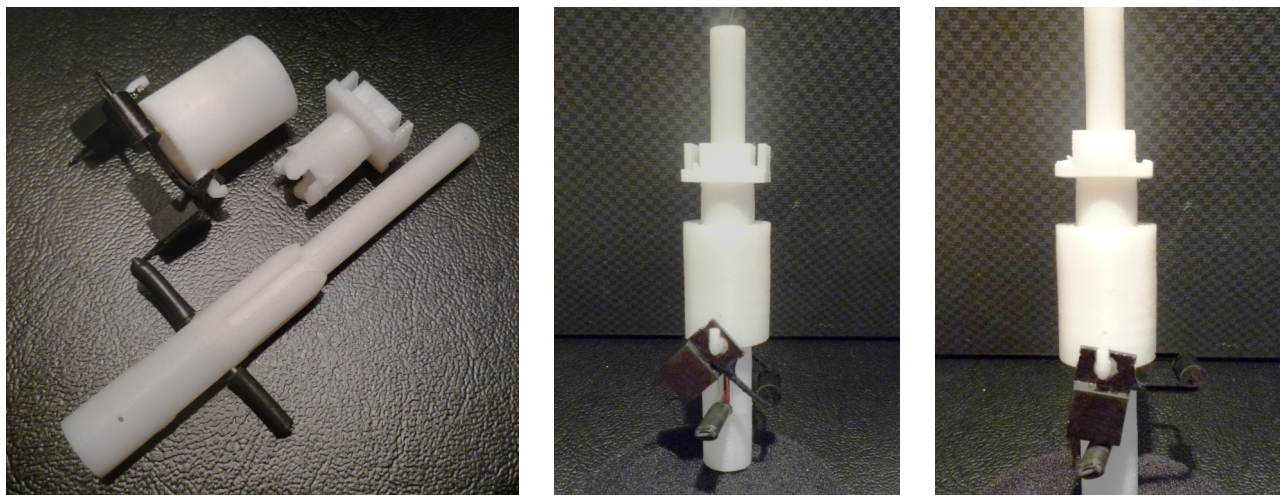


Figure 4.13: The final prototype which meets all the requirements. This exemplar still has some metal parts which will be replaced by plastic in the extended prototype.

The performance is considered good enough to build an extended prototype based on the developed design. The metal parts are replaced by plastic ones and can be further optimised according to their shape. The teeth are also further optimised. By placing more teeth it is possible to make the mechanism even more reliable: an additional set of teeth makes sure the pixel always turns exactly one step ahead. The mechanism is designed never to fail.

Both the row motor and the column motor are connected to all the corresponding pixel units by steel wires. The wires must not be expandable in order to allow accurate triggering. The row motor does not need to be strong as it is only pulling the light weighted part of the pixel unit. The column motor is not necessarily designed very strong either, because it lifts only activated pixels. The number of activated pixels at one time depends only on the mode of operation. By activating more pixel rows at the same time the change of the motif can be handled faster, but stronger column motors are needed.

The extended prototype could not be constructed by the print of the thesis. Nevertheless the Appendix provides a full parametrical model in GML, making it possible to adjust and directly print out a prototype. The final GML model also has some changes in the detailed design. The vertical grid is no longer made of rods, but rather it is a hanging of spring wires. Spring wires are flexible and do not run the risk of being bended. The display device is easier to install and the durability is higher. The horizontal activation rod is replaced by a rotary axis. It answers the same purpose and makes the activation slightly easier and more robust. By not using a linear activation, but a rotary instead, it is now possible to give stability to the construction. It can also be used to maintain the distance between the pixels, which is important because the pixels must not jam each other.

A mentionable drawback in terms of operation is the fact that this concept is only designed to turn in one direction. In the worst case for n pixel side faces, the pixel must be turned $n - 1$ times in order to expose the right side. During these turns the other sides are visible and may disturb the whole motif.

Chapter 5

Colours and Images

This chapter shows some of the diverse possibilities of operation. The field of application and the desired quality in different matters are decisive for on the customizations in the first place. The settings to decide are the following:

- Number of pixels that make up the image (aka resolution)
- Size of each pixel (aka dpi)
- Number of side faces a pixel has (similar to colour depth)
- Print on each face of the pixel (similar to colour palette)

Resolution, pixel density and colour depth are attributes well known from all kinds of display devices. They are to define in the first place and can not be changed after installation (except perhaps for the resolution by adding more display modules). These attributes have impact on the resulting quality, while the latter, the print on the pixels, is the crucial part of customization. Here it is possible to give the display a special purpose or an artistic aspect. The liberty to design each face of each pixel individually offers an interesting playground. It is even possible to exchange the pixel side faces every once in a while without great effort.

The following description of possible settings gives an idea how the whole device can be designed regarding the variables above. The provided visual examples in Section 5.1 and 5.2 are automatically generated with two especially implemented simulation programs.

5.1 Application Potential Through Specific Configuration

A conventional pixel is able to show between two (monochrome) and a few million (true-colour) colours. However, the pixels used here are not conventional and they have only a few side faces (two to four as proposed). Similar to a dot-matrix-display the possibilities are very limited if the resolution is not very high. Figure 5.1 shows an example for this simple configuration. But precisely because of the fact that these pixels are not conventional, it can be shown more than simple colours. This simple idea offers a wide range of potential to show all kind of motifs.

The examples of application in this section are made presuming medium to low resolution and two to four pixel faces but most of them can be adapted to any number of side faces.

5.1.1 Different Patterns Instead of Colours

Instead of painting the pixel faces with different colour shades, different shapes or tiny images can be used as well. It may also be advisable to mix several colours on one face. These settings work perfectly for text, simple patterns or simple decorations around a window, for example. There is potential for individualisations to meet someone's special wishes. Figure 5.2 shows some examples of how a pixel's face might look like and how it affects the result.

5.1.2 Different Patterns on Individual Pixels

Developing this concept, it is evident that not every pixel needs to be configured equally. Only making sure that the corresponding faces of all pixels are similar in colour, brightness or pattern shape can show the same pictures as above in a more artistic and more eye-catching way. Again there are plenty of settings thinkable. Figure 5.3 shows how such a configuration might look like. Like a mosaic, every single pixel represents a face while the whole arrangement forms a text.

5.1.3 A Motif as Background

The background does not necessarily have to be a uniform white tone. As the possibility exists one can also arrange the background pixels to be an image. The whole façade then shows always the same picture as background, and changing a pixel alters this tile in terms of brightness, contrast, saturation or hue. Also other ways of modification are possible. Figure 5.4 shows on an example of a corporate logo how such a configuration looks like.

5.1.4 Several Motifs Combined

These examples still do not take advantage of all the potential. The pixels can further be configured in a way that they show an image all together like a puzzle. As many faces as the pixels have, as many 'puzzles' can be shown. At first this idea did not seem very useful, but with wisely chosen and carefully designed motifs, you can generate stunning effects. Find some examples in Figure 5.5.

5.1.5 Specialised Motifs

These examples of application (Figure 5.6) show very specific settings which are designed to display a single motif. This motif, however, is highly modifiable in a predefined way. Observing the first example you can see that with only three pixel side faces it is possible to show eight different symbols for weather descriptions: sunny, cloudy, rainy, frosty, snowy, stormy (with and without rain) and stormy snowy. Depending on the ingenuity of the implementation there is a huge number of possible combinations to show different information. The theoretical maximum of motifs possible to show is $m = c^f$, where c is the number of possible motifs, f is the number of pixel side faces and p the total amount of pixels (resolution).

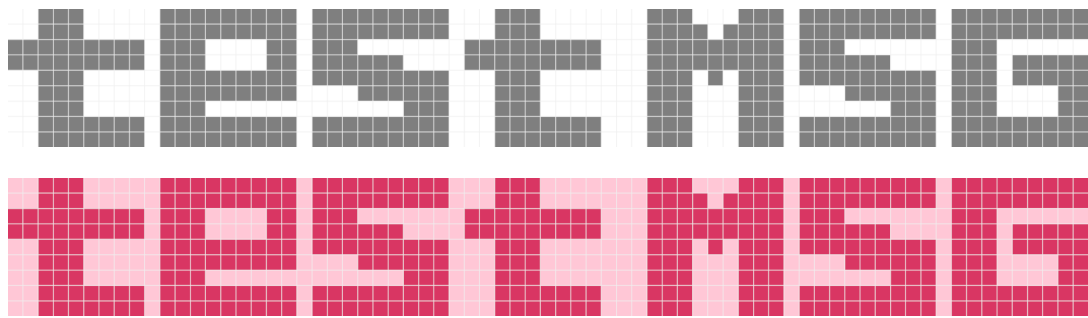


Figure 5.1: This pixel configuration is as innovative as a dot-matrix-display. With this small resolution the visual effect is still poor.

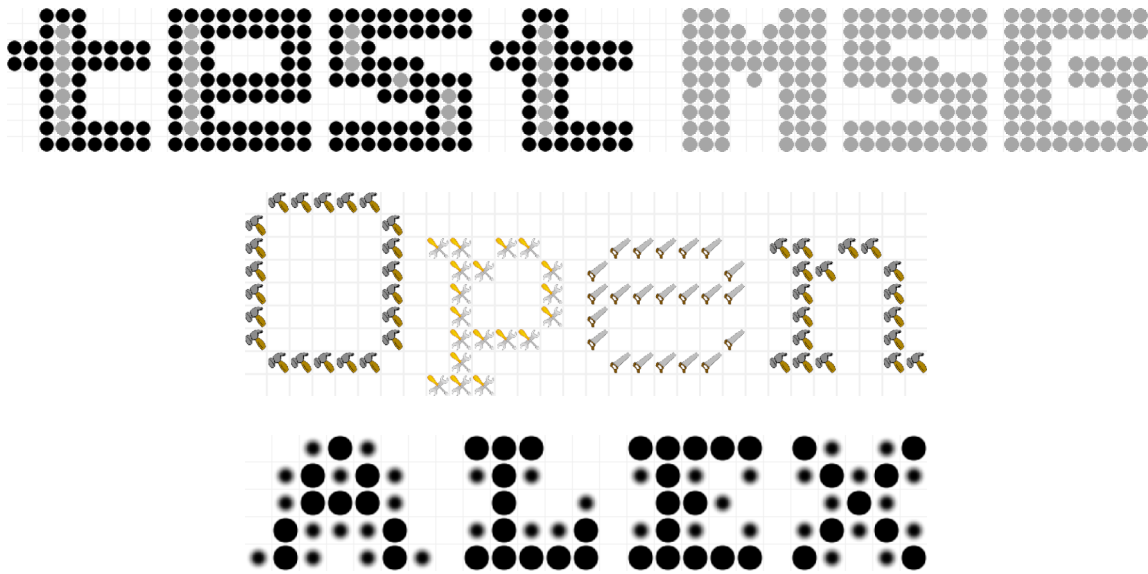


Figure 5.2: By introducing simple shapes or symbols the display gets characterised and the visual effect is more interesting.



Figure 5.3: These examples show mosaics where every pixel is designed individually. Every pixel is an image itself and contributes to the overall image (Photos taken from Google image search).



Figure 5.4: This example has a constant background while the pixels faces vary in brightness and contrast (from Microsoft®).



Figure 5.5: By combining several wisely overlaid motifs the visual effect can be increasingly artistic (Photos taken from Google image search).

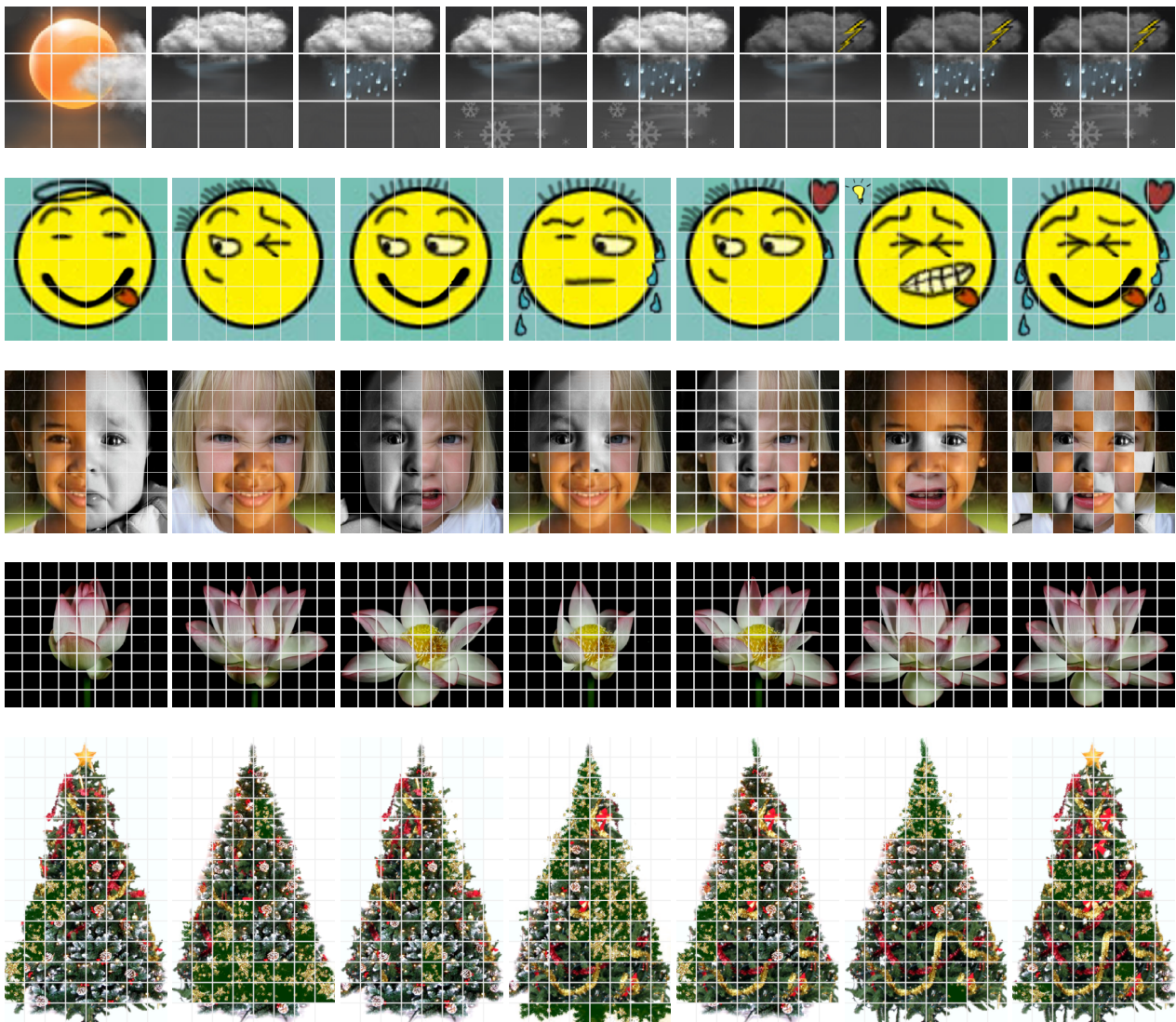


Figure 5.6: These examples show configurations especially fitted to certain applications. Within the given limits the motif is highly customisable (Pictures taken from Google image search).

5.2 Application Potential Through General Configuration

Section 5.1 has shown some special configurations which only allow certain motifs. In order to be able to show general content like photos, an other configuration must be chosen. The following sections describe the required image processing and different pixel configurations.

5.2.1 Gamma Correction

In computer science, colours are often denoted in the RGB colour space as $0xrrggbb$ in hexadecimal numbers with a range of 0..255 for every channel. It is, however not the right domain for mathematical operations on colours. Gray with half the intensity than white is by definition a mixture of black and white tiles (chequerboard pattern). The corresponding RGB code is, however, not $0x808080$, but $0xBABABA$. The intensity of a colour is not directly convertible into the RGB colour code. The relation between these two domains is not linear and the conversion between them is called *gamma compression* and *gamma expansion*. The gamma correction formulae are [rB]

$$I = \left(\frac{v}{255}\right)^\gamma \quad v = I^{1/\gamma} \cdot 255$$

, where v is the value of a channel in RGB space and I is the corresponding intensity. The default value for $\gamma = 2.2$. From now on the colours denoted in luminosity are formatted like (r, g, b) and every channel's range is within 0..1. All calculations dealing with colours must be made in the luminosity domain in order to compute correct mixtures. This means that all pixels and colour palettes must be gamma compressed before quantising and dithering. Afterwards, before outputting the resulting image it must be gamma expanded again.

5.2.2 Colour Mixture

This section describes basic colour mixing rules taken from [KüpB] and [Küpa]. It is relevant for the next sections. The human eye is sensitive to the three fundamental colours red, green and blue. By combining them, eight extreme colour sensations are possible to perceive. These are black (K), white (W), red (R), green (G), blue (B), cyan (C), magenta (M) and yellow (Y) and form the basis of integrated colour mixture (Figure 5.7). Using only these eight basic colours every



Figure 5.7: The eight basic colours for integrated mixture.

R	G	B		
5E	5E	5E	5E	W
3D	3D	00	3D	Y
47	00	00	47	R
00	00	00	1B	K
E3	9B	5E	FF	

Figure 5.8: An example of how a colour is split up to four of the eight basic colours of integrated mixture.

colour can be mixed. Figure 5.8 shows an example. The colour $0xE39B5E$ (hexadecimal notation of RGB) is a mixture of $0x5E$ parts white ($0x5E5E5E$), $0x3D$ parts yellow ($0x3D3D00$) and $0x47$ parts red ($0x470000$). To be formally correct the black part has to be considered as well. It is the missing part to 100%: $0xFF - 0x5E - 0x3D - 0x47 = 0x1B$. The yellow and red portions sum up to $0x84$ which is called the chromatic portion. The ratio between the two colours is 1 : 1.16 and is called chromatic type. The achromatic portion is $0x5E(W) + 0x1B(K) = 0x79$ and the achromatic type is 1 : 3.48. The ratio between chromatic and achromatic portion (1 : 1.09) is stated as chromaticity degree. Like this the integrated mixture provides the possibility to mix every possible colour with four of the eight primary colours.

The colour mixture applied in this project works basically like the integrated colour mixture, but is not exactly the same. Here, when mixing colours of two neighbouring pixels the colours are obviously not directly mixed, but only when seen from a certain distance the two colours blur to a single colour. This happens when the human's retina resolution power is exceeded so that the fine details of the reflected light mix into a homogeneously perceived colour shade. Figure 5.9 shows two examples how the so called *optical mixture* is perceived simulating different distances to the observer.

A combination of red and green, however, does not lead to a saturated yellow. I.e. it has not the full intensity as the basic colour yellow in Figure 5.7. This fact is explained through the *luminosity*. If the light reflected by a surface is seen as amount of particles it is obvious that yellow (1, 1, 0) reflects more such particles than an optical mixture between red and green $\frac{(1,0,0)+(0,1,0)}{2} = (0.5, 0.5, 0) \hat{=} 0xBABA00$. Because of this loss of luminosity, when combining colours it is not possible to mix every colour unless all eight basic colours are available for mixture. Figure 5.10 shows the example trying to mix basic colours.

With all the eight basic colours it is possible to approximately mix the colour (0xE39B5E). The coded colour 0xE39B5E after gamma compression is denoted as (0.77, 0.33, 0.11). For this example nine pixels are needed to be able to achieve the colour with good approximation. The table in Figure 5.11 shows the composition of basic colours and how they sum up to the desired luminosity and tone. Figure 5.12 shows the 3x3 pixel set with the calculated number of each colour and how it optically mixes to the desired colour.

The process of mixing can be more complex depending on the composition of the colour to mix. For example the colour (1, 0, 0.05) contains 20 times more red than blue which means that an area of 20 pixels is needed (1 magenta pixel and 19 red pixels) to achieve the exact same colour shade. An area of 20 pixels is, however, not quadratic and therefore not possible to tile as in the former example. These constraints demand approximations and the defining of preconditions when automating the mixture, i.e. designing the quantization and dithering algorithm (Section 5.2.3 and 5.2.4). It is also understood that when more pixels are used to mix a colour, the resolution becomes lower.

Additionally the presented display device does not generally allow the use of all eight basic colours, but rather two to four (as proposed in Section 3.1.3) per pixel. This problem is solved by either using the design for more pixel side faces (Section 3.1.3, Figure 3.7) or by choosing a compromised colour palette from Section 5.2.5.



Figure 5.9: Mixture of red and green resulting in yellow.

FF0000	+	00FF00	+	0000FF	=	9B9B9B
000000	+	000000	+	000000	=	000000
FFFF00	+	FF00FF	+	00FFFF	=	D4D4D4
FFFFFF	+	FFFFFF	+	FFFFFF	=	FFFFFF
00FF00	+	FF0000	=	BABA00		
FFFF00	+	FFFF00	=	FFFF00		
FF00FF	+	FFFF00	=	FFBABA		
FF0000	+	FF0000	=	FF0000		

Figure 5.10: When trying to mix yellow or white, the attempt fails using optical mixture because the loss of luminosity is inevitable. On the other hand black or red can not be mixed like this because unwanted luminosity affects the result.

R	G	B	
1	1	1	W
1	1	0	Y
1	1	0	Y
1	0	0	R
1	0	0	R
1	0	0	R
1	0	0	R
0	0	0	K
0	0	0	K
0.77	0.33	0.11	

Figure 5.11: This table lists the basic colours and their amount needed to optically mix the desired colour. The bottom row represents the nine pixels averaged.

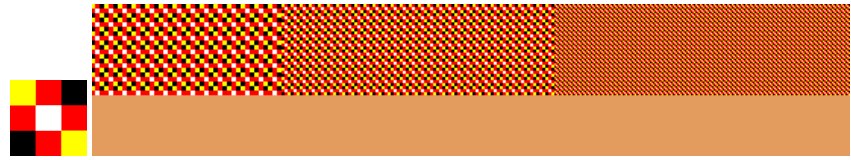


Figure 5.12: The tile on the left represents the calculated mixture of basic colours. The optical mixture on the right results in the same colour as before $(0.77, 0.33, 0.11) \Leftrightarrow E39B5E$.

5.2.3 Quantisation

In the case of monochrome black-and-white processing, i.e. a grey-scale image is reduced to only black $0x000000$ and white $0xFFFFFFFF$, the quantisation algorithm of tresholding is applied. The upper half of the grey-scale palette is set to white and the lower to black.

When introducing an additional shade of grey to the target colour palette (for example $0x808080$), the procedure stays the same: the colour values are just rounded to the closest colour in the palette. The procedure is the same for any number of grey scales.

In coloured images the colour space is three-dimensional and, depending on the output colour palette, they can not be treated separately. The problem when doing the quantisation for every channel separately is that the target colour palette must include all mixtures of all combinations of the colour palettes from the three channels. For example, if every channel is quantised to two shades (zero and full saturation), the target colour palette must include all of the eight basic colours (Figure 5.7).

For a general output colour palette other calculation methods are preferred. The colour to quantise is compared to all available colours in the colour palette and the mathematically nearest is picked. As criteria, the euclidean distance is calculated. The distance can be computed for example in the HSV space or in the RGB space. Here the RGB space is used:

$$d = \sqrt{(red(C_1) - red(C_2))^2 + (green(C_1) - green(C_2))^2 + (blue(C_1) - blue(C_2))^2}$$

d is the distance between the colours C_1 and C_2 . The three colour channels are treated completely separated and the channels have no influence among each other. In some cases this is not satisfying, for example if the colour palette includes only white, red and green but yellow has to be quantised, this simple algorithm can not decide between white, red and green because they all have the same distance in the RGB colour space (Figure 5.13). The right way is rather to

Original color C_1	Quantised color C_2	$red(C_1) - red(C_2)$	$green(C_1) - green(C_2)$	$blue(C_1) - blue(C_2)$	Error
FFFF00	FFFFFF	00	00	-FF	FF
FFFF00	FF0000	00	FF	00	FF
FFFF00	00FF00	FF	00	00	FF
FFFF00	BABA00	45	45	00	62

Figure 5.13: Quantising yellow to white, green or red results in the same error (distance). The last row shows the error when mixing green and red optically.

choose red and green alternatively so that a chess pattern of the two colours mix up optically to yellow $((0.5, 0.5, 0)$ or $0xBABA00$). The algorithm has thus to be implemented in a way that it considers spatial combination of pixels in order to obtain low error. With the simple threshold algorithm the desired outcome can not be achieved because it only considers one pixel at a time.

In the general case the subsequent dithering algorithm covers the processing regarding this problem. But as described in Section 5.2.4 there are special cases where dithering does not help and already the quantisation process has to prevent the occurrence of these cases.

To solve this problem, the colour palette for the quantisation and subsequent dithering is extended. Every colour from the palette is mixed with all the others in order to obtain the theoretical available colours when considering optical mixture of two neighbouring pixels. All the algorithms run normally and the previously described problem is solved. Before passing the processed image to the output, all these temporarily added pixels are replaced by available colours from the original palette. For instance the previously introduced mixture of red and green has to be replaced either by red or green. If two or more of those yellow pixels accidentally lie next to each other, the replacement is a red green check pattern and the visual appearance is again the same. Other constellations like single yellow pixels can not be replaced without causing a certain error but choosing the best replacement, taking into account the neighbouring pixels as well as adding a random factor, again improves the visual authenticity.

The alternative solution is to reduce the resolution of the image before processing the picture, do the computations on the small image with an enhanced quantisation algorithm which takes optical mixture of pixels into account and therefore generates the output in its original size. Although the effective resolution stays low and some details are lost. This algorithm was designed on paper only and was not implemented.

5.2.4 Dithering

Displaying an image with a very limited colour palette has great effect on the quality. The quantisation throws away a lot of information and colour shades may get lost completely. Flat areas of the same colour or colour bands appear instead and details disappear. The colours most probably appear significantly different than in the original image. In order to improve the appearance of a digital image with limited colour depth, dithering is used. Using the same colour palette dithering improves the image quality significantly to the human eye. In general the dithering process analyses the quantisation error for single pixels and distributes it to the neighbouring pixels. Like this, the illusion of higher colour depth is created because the human eye perceives optically mixed colours [Wika].

Newest techniques combine the processes of quantisation and dithering rather than doing it sequentially (for example [FGB*98]). These combined algorithms are able to adapt the colour palette. An optimised colour palette leads to much better image quality. This, however, is only limited applicable for this thesis, because the colour palette i.e. the pixels mounted on the wall are not adaptable to fit one special image. They must apply for a wide range of images once installed. Thus, the task of choosing the right colour palette for this display device in the first place is crucial (Section 5.2.5).

The most popular dithering algorithm is called Floyd-Steinberg and was published in 1976 [FS76]. The algorithm is still prevailing due to its simplicity and its overall fairly good quality. Based on this principle variations, adaptations and revisions like 'Atkinson', 'Jarvis, Judice and Ninke' or 'Stucki' emerged. They all do the same job with the only difference that they use other diffusing matrices (see Figure 5.14). The diffusion matrix defines how much of the quantisation error is

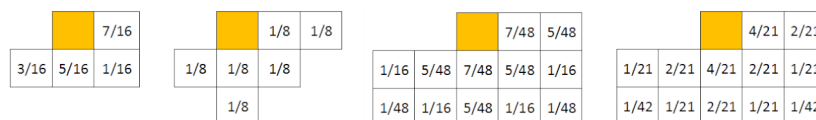


Figure 5.14: The matrices defining which part of the error to pass to which pixel: Floyd-Steinberg; Atkinson; Jarvis, Judice and Ninke; Stucki.

passed to which neighbouring pixel. This is done for every pixel from top to bottom with alternating processing direction left-to-right and right-to-left. This so called *serpentine* parsing prevents some artifacts.

Another approach does not define these values as constants, but chooses the distribution balance depending on the actual value of luminosity. The Floyd-Steinberg error diffusion algorithm produces harmful artifacts in highlights and in dark areas as well as at certain intensity levels [Ost01]. Consequently the diffusion matrix is made dependent on the intensity of the input pixel.

The output of these different algorithms varies only in detail and in general it is not possible to say which one is better. The behaviour is dependent on the input picture and different viewers may prefer different results. The Atkinson algorithm for example does not propagate the full error, but only 75%. This leads to a loss of contrast for high and low intensities but to a better contrast in the mid-tones. It is thus best – if possible – to provide the images in all dithered versions and to let the user choose his favourite. Figure 5.15 shows an example: the only difference between them is the dithering algorithm and the user could just click on the image he/she likes to be shown on the façade display.

A common problem when using very poor colour palettes arises due to the clipping. The colour's magnitude is limited to its range (in this case 0..255) and a additional error outside these limits is simply neglected. Thus, if, like in the previous example (Figure 5.13), a set of yellow pixels is quantised to red for instance, the error to diffuse is 0x00FF00 (the green channel has full error). However, adding up the error to the yellow neighbouring pixels does not affect them at all because

their green channel is already fully saturated. The added error gets clipped immediately and the dithering has no effect. If – instead of clipping – the values are normalised, the algorithm behaves better in this special case, but in general it leads to other not wanted distortions and artifacts. The previously (in Section 5.2.3) discussed algorithm solves the problem more elegantly.



Figure 5.15: These images are generated using different dithering algorithms: Original image, 'Floyd-Steinberg', 'Atkinson', 'Jarvis, Judice and Ninke', 'Stucki' and 'Variable Constants'. (Original image from Dominique Tous-saint)

5.2.5 Colour Palette and Examples

Given the very constrictive number of pixel side faces there is no solution to the general colour palette. It is simply not possible to show all kinds of images with only three or four colours. Even if more than four colours are used as described in Section 3.1.3, it will not reach the quality of a regular LCD screen as these operate with color depths of 8 bit and more. The aim is thus, to find colour palettes to meet certain criterias and thereby to concentrate on a limited set of images to show. With four pixel side faces this set is quite big already.

The pixel configurations in this section are presented on some example images with a resolution of 100x100 pixels and are all generated with the especially implemented software.

Two pixel side faces do not leave much space for innovation. Figure 5.16 shows grey-scale examples for convenience. It is recommended to use one colour as background equally for every pixel. The second pixel face is commonly black or another foreground colour, but it could also be varied over different pixels in order to bring in more than just one foreground colour. Such a special configuration would meet some special client's wishes but does not show satisfying results in the general case. Rather it is best to use just two colours. Black-and-white gives good results if proper dithering is done.

Three pixel side faces is the most convenient number in terms of mechanical function and good results can be achieved through proper tuning. First, for handling grey-scale images grey is introduced on the third pixel's face additionally to black and white. Figure 5.16 shows some examples with different grey-scale palettes. With black, white and middle grey (■□□) the resulting image is already a lot better than the monochrome example from before. To further improve the perceived quality the palette can be extended by more grey tones. As the following examples show, the pixel configurations vary over space and different shades of grey are introduced. The pixels show two to four different grey tones which are equally distributed among the display pane.

As the colour palette is changing depending on the pixels location, some other thoughts and algorithms have to be reconsidered. The quantisation algorithm needs to be adapted. The distribution of different pixels might create artifacts. How to prevent this is described and handled in Section 5.2.6.





The third face makes it also possible to introduce colours. Every pixel can have either red, green or blue additionally to black and white (■□■□■□). This way it is possible to show colours while still clear black and white can be shown (see Figure 5.17). Black and white are important for the contrast, the contours and details. Texts, for example are best to be depicted in black over white.







Omitting either white or black in order to produce more saturated colours offers a lot of possibilities. The most approved colour palettes are shown in Figure 5.17.









The second configuration (■□■□■□) is meant to have either black or white on every second pixel and also two of the three primary colours equally distributed (every colour is presented on two out of three pixels). This configuration is a good compromise and produces average colours and contrast.

The colour palette including all basic colours except black (■□■□■□) is optimised for bright motifs. By replacing half of the white pixels by black (■□■□■□), the balance between black and white is equalised but no clear white or dark black can be shown. The configuration without white (■□■□■□) can be used for dark images.

The last example in Figure 5.17 is optimised for reddish images, as an example for client specific configuration. The examples either have good contrast and colour density or are specialised for clear or dark images, respectively. For a general colour palette with better performance the number of pixel side faces has to be augmented.

Four pixel side faces. Even though setting up more than three faces have its disadvantages (see Section 3.1.3), the option is still handled here because the gain in image quality can be quite big. With four faces it is possible to place three colours and a background colour on only one pixel. Like this, good colour reproduction is possible while a clear background colour such as black or white can be shown. The outcome with the combination of red, blue, green and white (□) is quite good. Dark grey can be mixed with the three colours and every colour is depictable in full saturation. However, no black or dark colours are possible to show and the mixing of yellow, cyan and magenta is not satisfying.

The second configuration (□) introduces black as well as the three missing basic colours. It results in a less clear white, though, and none of the colours can be displayed in full saturation.

The third configuration (□) improves the black and white tones but compromises the colour reproduction. The last configuration again is specialised for reddish images.

Five pixel side faces, as mentioned in Section 3.1.3 are not really realisable but every single side face multiplies the number of possibilities and thereby the out-coming image quality. Therefore some more examples are provided (Figure 5.19 to show the theoretical benefit of every additional side face.

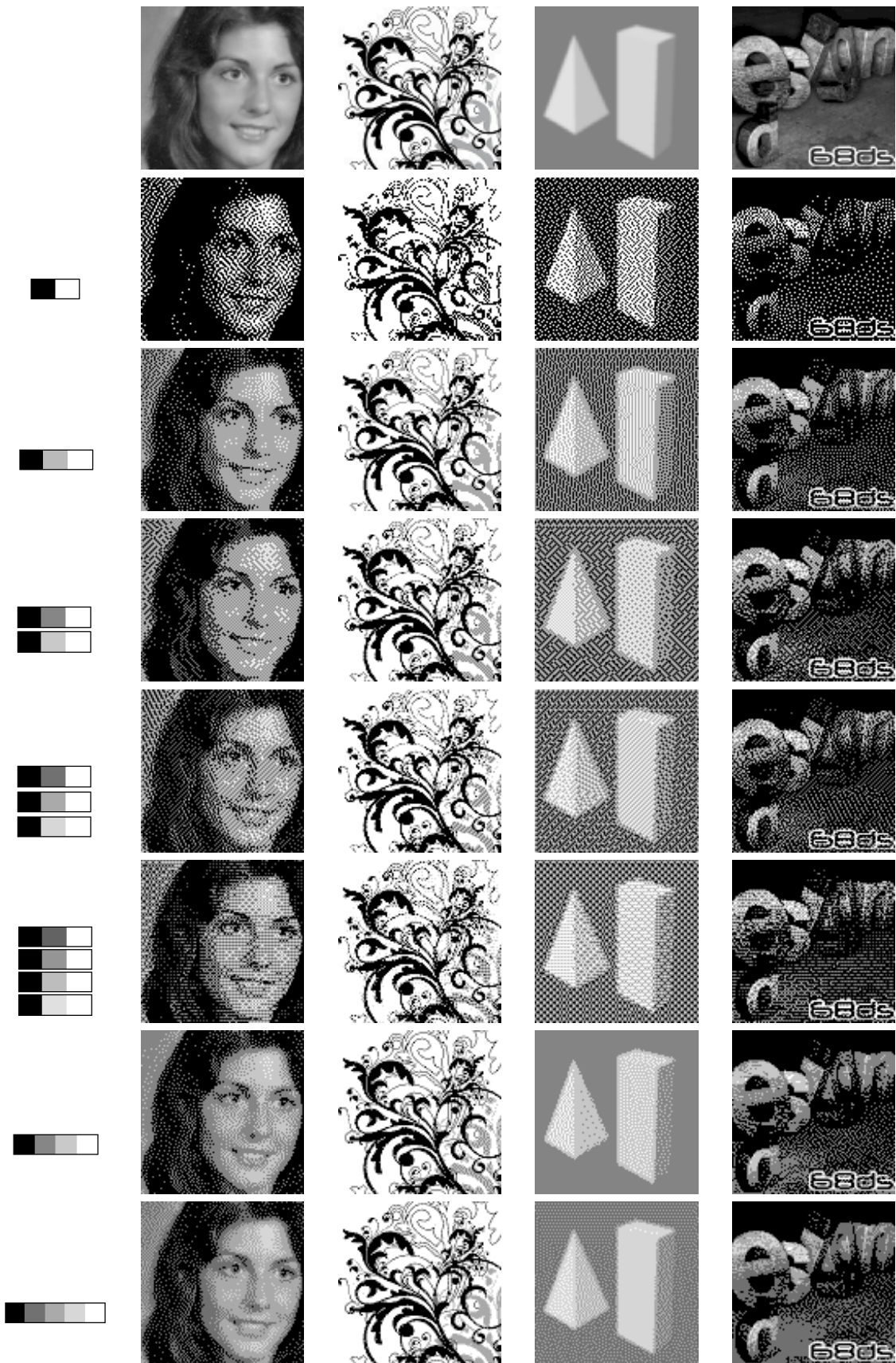


Figure 5.16: Grey-scale examples with two to five pixel side faces (the rightmost is taken from www.68ds.com).

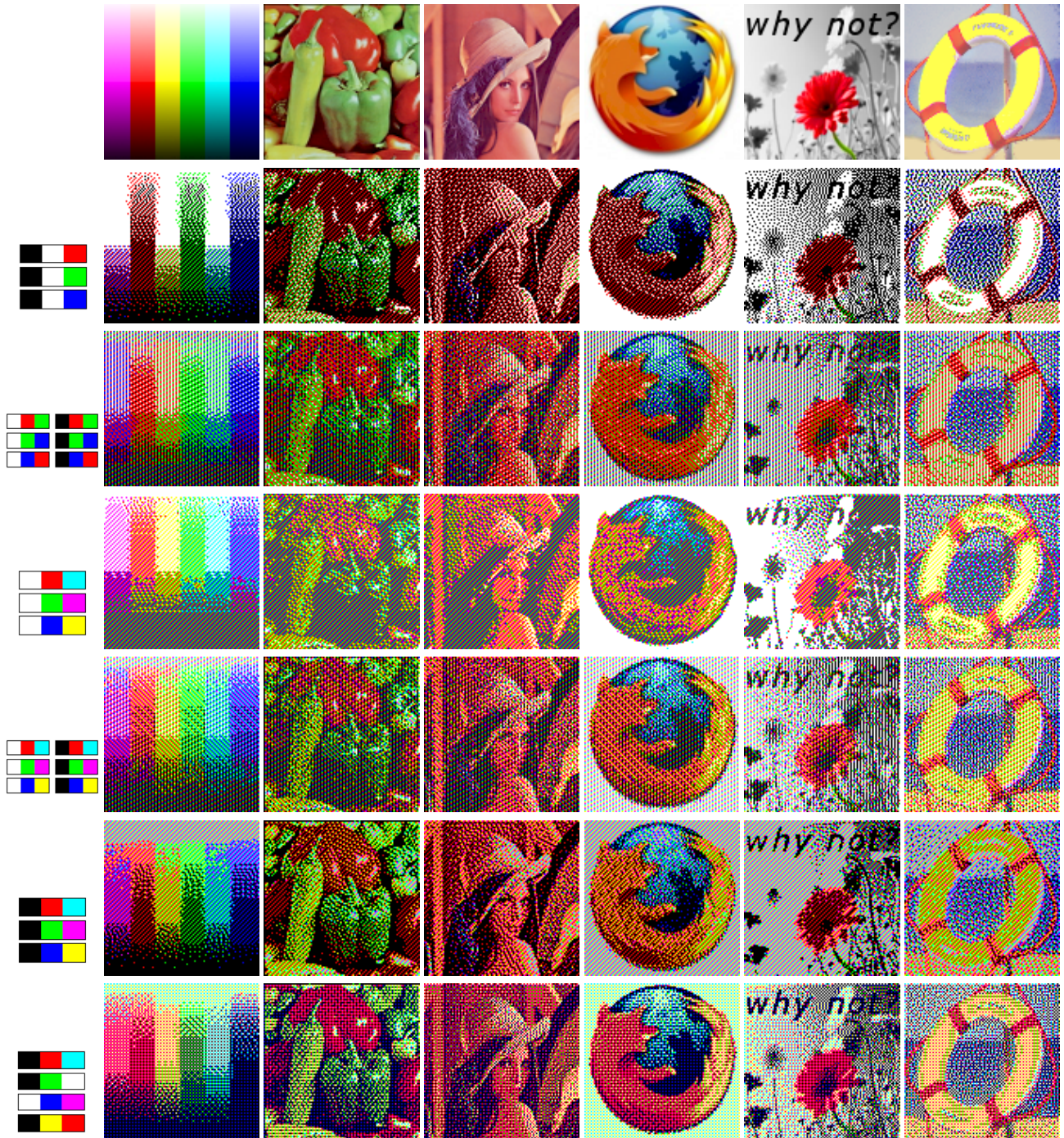


Figure 5.17: Colour examples with three pixel side faces.

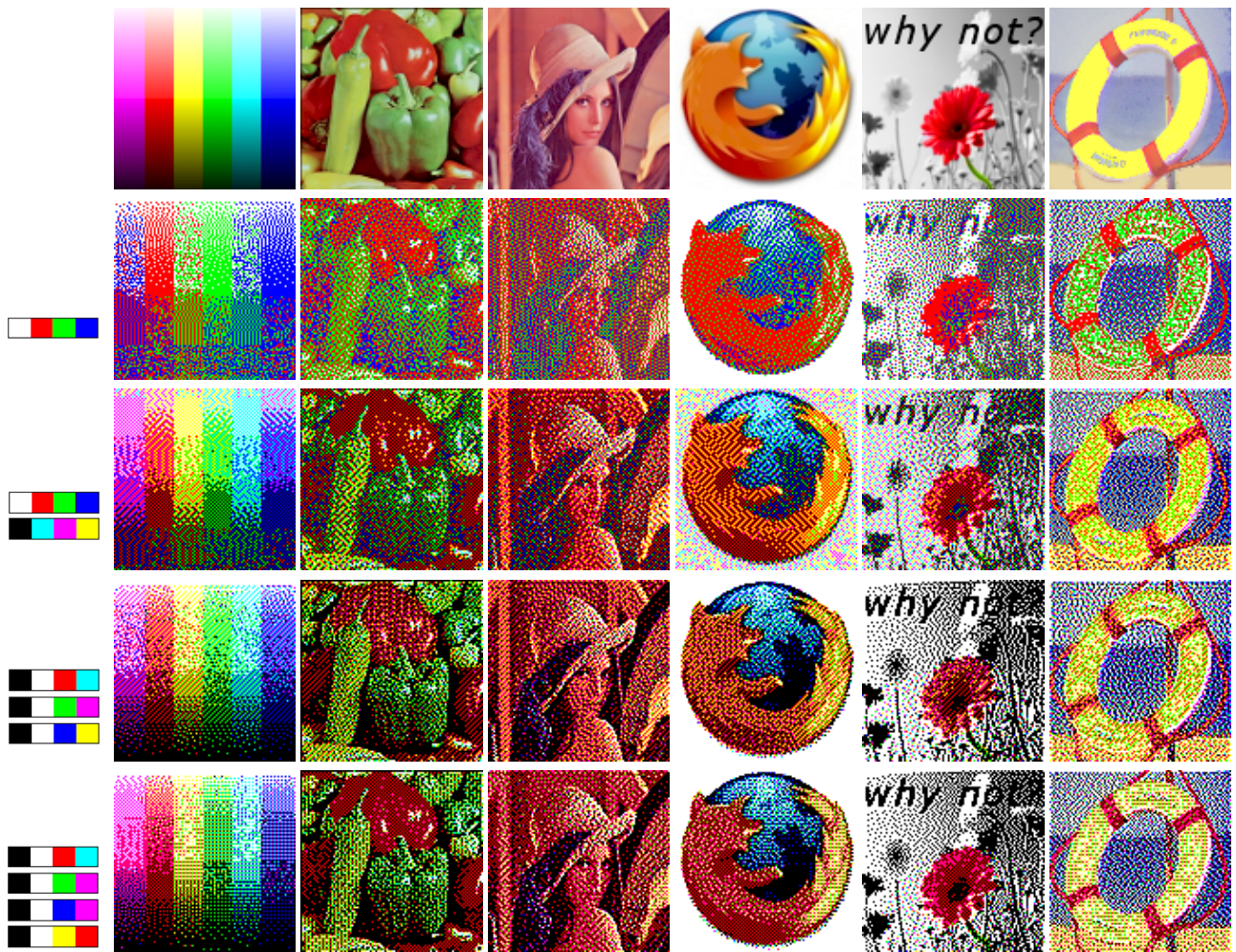


Figure 5.18: Colour examples with four pixel side faces.



Figure 5.19: Colour examples with five pixel side faces.

5.2.6 Pixel Distribution

This section is only relevant if colour the palette (from Section 5.2.5) implies several pixel configuration which is not equal for all the pixels. Mixing different configured pixels in a display can provoke artifacts if the distribution of the different pixels is not chosen properly. The proposals for the three, four and six different pixel configurations are found in Figure 5.20. Alternatively, instead of using a regular pattern, the pixels could also be distributed randomly. This method provokes artifacts but removes the regularity.

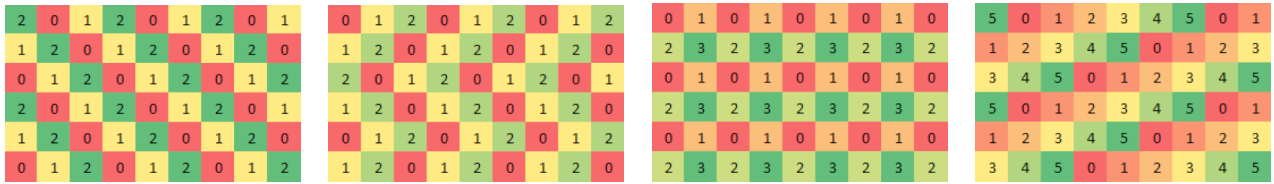


Figure 5.20: In order to prevent artifacts the distribution pattern for different configured pixels has to be chosen carefully.

Chapter 6

Discussion

6.1 Discussion: Strengths and Weaknesses

The goals set at the beginning of the work were defined properly and by keeping them in mind throughout the entire work, they were mostly fulfilled by the final prototypes. Some aspects, however, still need improvement or clarification. The price for the prototypes for example is not rated. The magnetic prototype is very likely to cost more than previously intended: For one magnet only, a 7 m long copper wire and an iron coil core are needed. Plus, the hanging, the cables and the mounting have to be considered. It is still to evaluate and it depends a lot on the way and quantity of production, but the price will most probably be above 1 cent per pixel. The final comparison anyway favours the mechanical design. The Magnetic Concept was meant to be simple and plain. It was surprisingly accomplished at a higher level by the Mechanical Concept.

The mechanical prototype has more potential: It consists of three parts which are all fabricable by die-casting which is a very inexpensive method of production. Also here it is not evaluated in detail, but it should be possible to get near the 1 cent per pixel.

The gap between pixels is a topic to be mentioned as a weakness. Not only the horizontal gap, but also the vertical gap have to be considered. Both the final prototypes need this vertical gap to work properly. With an optimised fabrication it can be reduced furthermore and in big scale it can even be neglected, but in comparison to other display devices it is a weakness that should not be neglected.

The scalability is an important aspect when dealing with display devices. The presented prototypes were built in different sizes and resolutions. Knowledge was gained by combining different configurations, but there was no possibility to actually scale one of these test objects. The prototypes are built for tests only and have 25 pixels at most. In order to scale it, the number of pixels has to be increased to about 500. That is a reasonable size for a pixel unit and is easily possible for both the Mechanical and the Magnetic Concept. Such units can then be stacked to a modular device of any size. This is generally unproblematic but implicates new modes of operation and more wiring.

The simple mechanics proposed in this work are, as expected, easy to fabricate and robust. It was, however, difficult to find the best materials and not all kinds of substance were available for testing. Nevertheless the functionality was proven and by further developing the prototypes they can still be improved.

The strengths of this display technology are the very low cost of purchase and operation. The technology is therefore available for a broad public. Concerning the legal situation, the display is not only affordable for private households, but also operable without constraints in legality. Comparing the display device technology to conventional display devices it may produce images with less quality or less flexibility, but still the strengths prevail and allow an owner of such a façade display device to exhaust all the possibilities in his/her own way and style. The proposed applications in Section 5.2 and 5.1 just give some ideas and are barely able to show all the potential this technology provides.

6.2 Future Work

The next steps in development extending this work are, as already mentioned, the realisation of more pixel side faces and the enhancement of the scalability. The former should be based on the proposal of Section 3.1.3. With these six or more side faces, the displayable content improves significantly without any loss of the other functionality. The latter, the improvement of scalability, is done by making the display device modular and easy to tile. To make this possible, a way has to be found to make the frames of the modules with its motors and/or cables as thin as possible. The Appendix provides a parametrical model in GML regarding these aspects. It could, however, not be printed out in 3D by the print of

the thesis.

The fact that the display device will be installed outdoors was considered during the design. Every design respects this crucial factor, but at the end the prototypes were built for testing only and not dimensioned for environmental influences. The next prototypes should include this important aspect in order to test the durability in reality. In general, future work also needs to be done in the optimisation of the construction in its very details. There is still a lot of potential to gain performance if the fabrication is tuned properly.

6.3 Conclusion

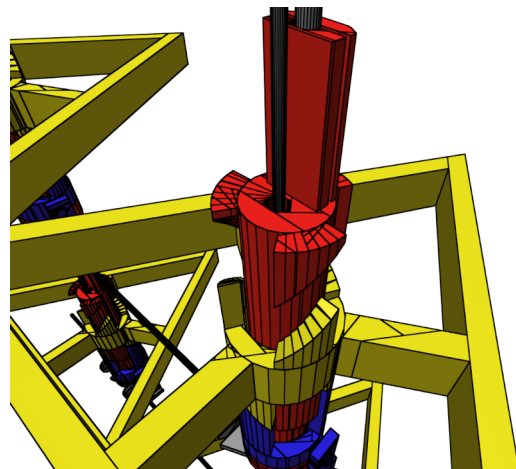
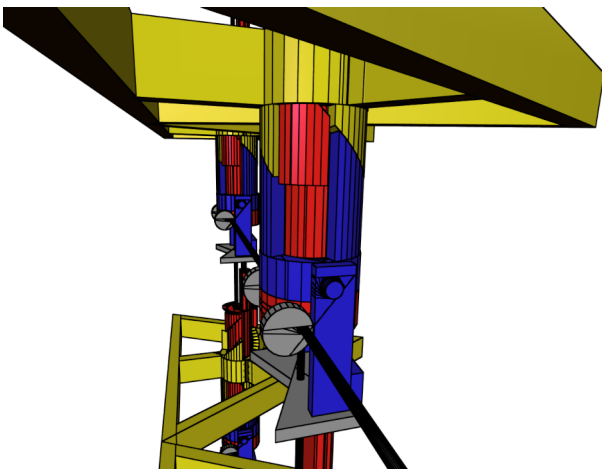
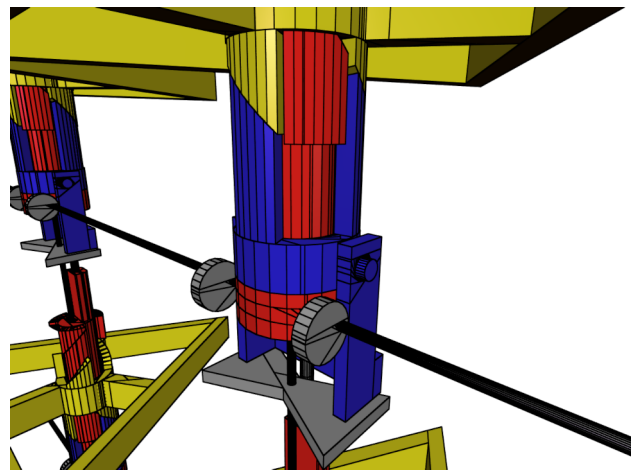
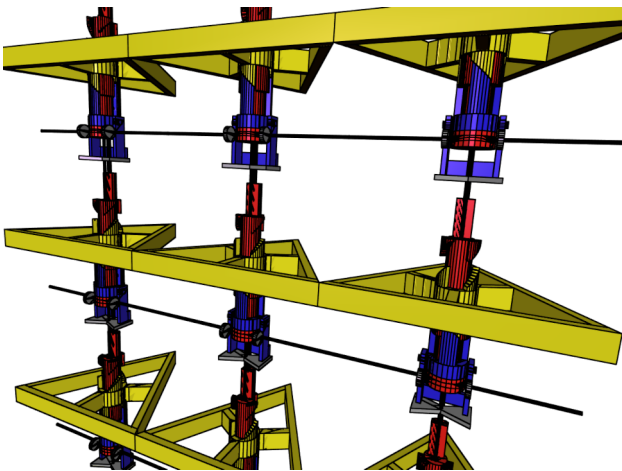
This work is considered as a success and the developed display device fulfils the requirements defined at the beginning. This work provides descriptions of all the development processes with all the refused designs as well as a detailed description of how the final design is assembled and how it works. The basic building instructions allow everybody to understand and copy the technology. Not only the hardware, but also the software is developed, proven and explained in this work and can be used for further research.

Not provided in this work, but available upon request, the software for simulation and control was implemented during this work. It is fully functional and essential for the planning and configuration of the display device before installation. All kinds of configurations can be tested in advance and the produced visual effects can be observed without any effort of prototyping. The GML model in the Appendix can be seen as the final solution for the given problem in terms of mechanical engineering.

Chapter 7

Appendix

The final design is modeled with GML and attached you find the source code, as well as some screenshots of the parametric model. It can be adjusted and scaled according to the actual needs and then be exported from the GML software in order to print it out. For more information on GML, please visit www.generative-modeling.org.



main

```

% this is the main item
% start generation of the model here

applet-clear
deleteallmacros
(1,1,1) opengl-background
clear
usereg
isPlay.parts begin
isPlay.tools begin

isPlay.parameters.parameter
KS

(0,0,0) !absolute_center

0 1 grid-count-z 1 sub {
size mul !dz
0 1 grid-count-x 1 sub {
size mul !dx
:absolute_center dup getX :dx add putX dup getZ :dz add putZ !point
:point grid { dup /stdBlack (0,0,0) 0 0 0 cp-po-setproperties cp-po-render } forall
:point part01 { dup /stdRed (0,0,0) 0 0 0 cp-po-setproperties cp-po-render } forall
:point part02 { dup /stdBlue (0,0,0) 0 0 0 cp-po-setproperties cp-po-render } forall
:point part03 { dup /stdYellow (0,0,0) 0 0 0 cp-po-setproperties cp-po-render } forall
} for
} for

```

parameter

```

% This item defines all the parameters for the model

usereg
25 /kseg edef
8 /kseg-deg-step edef
3 /tooth-count edef
0.3 /clearance edef
3 /clearance-deg edef
5.5 /move-dist edef
.065 /tooth-inclination edef

% for the tiling of units:
50 /size edef

% temporary parameters, for dependency reasons
3 /p21-sizez-temp1 edef
1.3 /p14-thick-temp edef

% PART01
% 1 main tube
32 /p11-sizez edef
2.5 /p11-radius edef
% 2 lower ring (end stop)
3 /p12-sizez edef
/p12-radius p11-radius def
/p12-thick p14-thick-temp clearance add def
% 4 lower teeth
/p14-offz p12-sizez p21-sizez-temp1 add move-dist add def
4.7 /p14-sizezmin edef
/below/p14-sizezmax edef
/p14-radius p11-radius def
p14-thick-temp /p14-thick edef
% 5 hole for vertical grid
1 /p15-offy edef
.5 /p15-radius edef
% 3 hold for main tube
/p13-offz p11-sizez def
8 /p13-sizez edef
2 /p13-sizey edef
3.5 /p13-sizez edef
.3 /p13-trench edef
0.3 p15-offy add /p13-offy edef
% 6 hole for vertical actuation wire
0.6 /p16-offy edef
.6 /p16-radius edef
% 7 hole for horizontal actuation wire
/p17-offz p12-sizez 2.0 div def
/p17-sizez p11-radius 2 mul def
-1.9 /p17-offy edef
.6 /p17-radius edef
% 8 upper teeth
360.0 tooth-count div 2.0 div !deg

```



```

    /p18-offz p11-sizez def
-0.5 /p18-sizezmin edef
    /p18-sizezmax :deg tooth-inclination neg mul p18-sizezmin add def
    /p18-radius p14-radius def
    /p18-thick p14-thick def

% PART02
% 1 inner ring
    /p21-offz p12-sizez def
p21-sizez-templ /p21-sizez edef
    /p21-radius p11-radius clearance add def
    /p21-thick p14-thick def
% 2 teeth
    360.0 tooth-count div 2.0 div clearance-deg 2 mul sub !deg
    /p22-offz p21-offz p21-sizez add def
p14-offz p22-offz sub p14-sizezmin add 0.5 sub /p22-sizezmax edef
    /p22-sizezmin p22-sizezmax :deg tooth-inclination mul sub def
    /p22-radius p21-radius def
    /p22-thick p21-thick def
% 4 activation mechanism axis
    /p24-offz p21-offz p21-sizez 2.0 div add def
    /p24-offx p21-radius p21-thick 2.0 div add def
    2.5 /p24-sizez edef
    .65 /p24-radius edef
% 5 activation mechanism lever
    1 /p25-sizez edef
    3 /p25-sizey edef
    /p25-sizez p12-sizez p21-sizez add move-dist add def
    /p25-offz p25-sizez 2.0 div neg clearance add def
    /p25-offx p21-radius p21-thick add clearance add p25-sizez 2.0 div add def
    /p25-offy p25-sizey 10.0 div def
% 6 activation mechanism lever join
    /p26-sizez p25-offx 2 mul p25-sizez add def
    /p26-sizey p25-sizez def
    /p26-sizez p25-sizez def
    /p26-offz p25-offz def
    /p26-offy p25-offy p25-sizey 2.0 div add p26-sizez 2.0 div add def

% PART03
% 1 upper ring
    22 /p31-offz edef
    -5 /p31-sizez edef
    /p31-radius p21-radius def
    /p31-thick p21-thick def
% 2 lower teeth
    360.0 tooth-count div 2.0 div clearance-deg sub !deg
    /p32-offz p31-offz p31-sizez add def
    -5 /p32-sizezmin edef
    /p32-sizezmax :deg tooth-inclination neg mul p32-sizezmin add def
    /p32-radius p21-radius def
    /p32-thick p21-thick def
% 3 upper teeth
    360.0 tooth-count div 2.0 div !deg
    0.5 /p33-sizezmin edef
    /p33-sizezmax :deg tooth-inclination mul p33-sizezmin add def
    /p33-offz p31-offz def
    /p33-radius p32-radius def
    /p33-thick p32-thick def
% 4 attachment for pixel flags
    2 /p34-width edef
    5 /p34-offz edef
    2 /p34-thick edef

% defined here, for dependency reasons
    /p14-sizezmax p22-sizezmin 0.7 sub def

% GRID
    1 /grid-count-x edef
    1 /grid-count-z edef

```

part01

```

% this item generates part 1 of the model - aka hanging

usereg
isPlay.tools begin

!point

% 1 main tube
:point
dup dup getZ p11-sizez add putZ
p11-radius

```

```

kseg
%p0, p1, radius, divisions
cylinder !main_tube

% 2 ring
:point
p12-sizez
p12-radius
p12-thick
kseg
% p0, tall, radius, thick, kseg
tube !ring

% 3 hold
:point dup getZ p13-offz add putZ dup getY p13-offy sub putY !p
:p
p13-sizez
p13-sizey
p13-sizez
simpleBlock !hold
:p
p13-sizez
p13-trench
p13-sizez
simpleBlock !trench
:point dup getZ p13-offz add putZ
p13-sizez
p11-radius
p13-sizez
kseg
% p0, tall, radius, thick, kseg
tube !bello
[:hold] [:trench] cp-csg-difference !hold
:hold :bello cp-csg-difference !hold

% 5 hole for grid
:point dup getY p15-offy sub putY
dup dup getZ size add putZ
p15-radius
kseg
%p0, p1, radius, divisions
cylinder !hole
[:main_tube] [:hole] cp-csg-difference !main_tube
:hold [:hole] cp-csg-difference !hold

% 6 hole for vertical actuation wire
:point dup getY p16-offy add putY
dup dup getZ size add putZ
p16-radius
kseg
%p0, p1, radius, divisions
cylinder !hole
:main_tube [:hole] cp-csg-difference !main_tube

% 7 hole for horizontal actuation wire
:point dup getZ p17-offz add putZ dup getY p17-offy sub putY !p
:p dup getX p17-sizez sub putX
:p dup getX p17-sizez add putX
p17-radius
kseg
%p0, p1, radius, divisions
cylinder !hole
:main_tube [:hole] cp-csg-difference !main_tube
:ring [:hole] cp-csg-difference !ring

% 4 lower teeth
[] !lower_teeth
0 1 tooth-count 1 sub {
!counter
[
:point dup getZ p14-offz add putZ
p14-sizezmin
p14-radius
p14-thick
360 tooth-count div :counter mul
360 tooth-count div :counter mul 360 tooth-count 2 mul div add
tooth-inclination
kseg-deg-step
%point height radius thick deg_start deg_end inclin kseg
tooth :lower_teeth ] flatten !lower_teeth
} for
:point dup getZ p14-offz add p14-sizezmax add putZ
(0,0,1)
planePN !plane
:lower_teeth { dup :plane cp-po-addplane } map !lower_teeth

```

```

:lower_teeth :main_tube cp-csg-difference !lower_teeth

% 8 upper teeth
[] !upper_teeth
0 1 tooth-count 1 sub {
  !counter
  [
    :point dup getZ p18-offz add putZ
    p18-sizezmin
    p18-radius
    p18-thick
    360 tooth-count div :counter mul
    360 tooth-count div :counter mul 360 tooth-count 2 mul div add
    tooth-inclination neg
    kseg-deg-step
    %point height radius thick deg_start deg_end inclin kseg
    tooth :upper_teeth ] flatten !upper_teeth
  } for
:upper_teeth :main_tube cp-csg-difference !upper_teeth

[
  :main_tube
  :hold
  :ring
  :lower_teeth
  :upper_teeth
] flatten

```

part02

```

% this item generates part 2 of the model - aka trigger

usereg
isPlay.tools begin

!point

% 1 inner ring
:point dup getZ p21-offz add putZ
p21-sizez
p21-radius
p21-thick
kseg
%p0, tall, radius, thick, kseg
tube !inner_ring

% 2 teeth
[] !teeth
0 1 tooth-count 1 sub {
  !counter
  [
    :point dup getZ p22-offz add putZ
    p22-sizezmin
    p22-radius
    p22-thick
    360 tooth-count div :counter mul 360 tooth-count 2 mul div add clearance-deg add
    360 tooth-count div :counter mul 360 tooth-count div add clearance-deg sub
    tooth-inclination
    kseg-deg-step
    %point height radius thick deg_start deg_end inclin kseg
    tooth :teeth ] flatten !teeth
  } for

% 4 am axis
:point dup getZ p24-offz add putZ !p
:p dup getX p24-offx add putX
:p dup getX p24-offx add p24-sizez add putX
p24-radius
kseg
%p0, p1, radius, divisions
cylinder !am_axis1
% symmetric
:p dup getX p24-offx sub putX
:p dup getX p24-offx sub p24-sizez sub putX
p24-radius
kseg
%p0, p1, radius, divisions
cylinder !am_axis2
[:am_axis1 :am_axis2] :inner_ring cp-csg-difference !am_axis

% 5 am lever
:point dup getZ p25-offz add putZ dup getX p25-offx add putX dup getY p25-offy sub putY
p25-sizez
p25-sizey

```

```

p25-sizez
% point, size_x, size_y, size_z
simpleBlock !lever1
:point dup getZ p25-offz add putZ dup getX p25-offx sub putX dup getY p25-offy sub putY
p25-sizez
p25-sizey
p25-sizez
% point, size_x, size_y, size_z
simpleBlock !lever2
% horizontal join
:point dup getZ p26-offz add putZ dup getY p26-offy sub putY
p26-sizez
p26-sizey
p26-sizez
% point, size_x, size_y, size_z
simpleBlock !lever3

% axis to cut out the lever
:point dup getZ p24-offz add putZ !p
:p dup getX size sub putX
:p dup getX size add putX
p24-radius clearance 2.0 div add
kseg
%p0, p1, radius, divisions
cylinder !axis
[:lever1 :lever2 :lever3] [:axis] cp-csg-difference !lever

[
  :inner_ring
  :teeth
  :am_axis
  :lever
] flatten

```

part03

```

% this item generates part 2 of the model - aka turner

usereg
isPlay.tools begin

!point

% 1 upper ring
:point dup getZ p31-offz add putZ
p31-sizez
p31-radius
p31-thick
kseg
%p0, tall, radius, thick, kseg
tube !upper_ring

% 2 lower teeth
[] !lower_teeth
0 1 tooth-count 1 sub {
  !counter
  [
    :point dup getZ p32-offz add putZ
    p32-sizezmin
    p32-radius
    p32-thick
    360 tooth-count div :counter mul 360 tooth-count 2 mul div add clearance-deg add
    360 tooth-count div :counter mul 360 tooth-count div add
    tooth-inclination
    kseg-deg-step
    %point height radius thick deg_start deg_end inclin kseg
    tooth :lower_teeth ] flatten !lower_teeth
  } for

% 3 upper teeth
[] !upper_teeth
0 1 tooth-count 1 sub {
  !counter
  [
    :point dup getZ p33-offz add putZ
    p33-sizezmax
    p33-radius
    p33-thick
    360 tooth-count div :counter mul
    360 tooth-count div :counter mul 360 tooth-count 2 mul div add
    tooth-inclination neg
    kseg-deg-step
    %point height radius thick deg_start deg_end inclin kseg
    tooth :upper_teeth ] flatten !upper_teeth
} for

```

```

} for

% 4 attachment for pixel flags
3 sqrt 6 div size mul !radius % incircle
3 !side_count
tooth-count 4 eq {
  size 2.0 div !radius
  4 !side_count
} if
tooth-count 5 eq {
  size 0.6881909602355 mul !radius
  5 !side_count
} if
:point dup getZ p31-offz add p34-offz sub putZ
p11-radius clearance add
:radius p11-radius sub clearance sub p34-thick sub
p34-width
p34-offz
90
:side_count
% point dist radius width height offturn count
star08 !star
:star :upper_ring cp-csg-difference !star

:point dup getZ p31-offz add p34-offz sub putZ
p34-offz
:radius p34-thick sub
p34-thick
:side_count
%p0, tall, radius, thick, kseg
tube !clamp

%flag
:point
size move-dist sub
:radius
0.001
:side_count
%p0, tall, radius, thick, kseg
tube !flag

[
  :upper_ring
  :lower_teeth
  :upper_teeth
  :star
  :clamp
  %:flag
] flatten

```

grid

```

% this item generates the grid and the horizontal and vertical actuator

usereg
isPlay.tools begin

!point

% vertical grid
:point dup getY p15-offy sub putY dup getZ move-dist sub putZ
:point dup getY p15-offy sub putY dup getZ move-dist sub size add putZ
p15-radius
kseg
%p0, p1, radius, divisions
cylinder !rod_v

% vertical actuator
:point dup getY p16-offy add putY dup getZ move-dist sub putZ
:point dup getY p16-offy add putY dup getZ move-dist sub size add putZ
p16-radius 2.0 div
kseg
%p0, p1, radius, divisions
cylinder !actuator_v

% vertical actuator disc
:point dup getY p16-offy add putY dup getZ move-dist sub putZ !pt
:point dup getY p16-offy add putY dup getZ move-dist sub 1 sub putZ !pb
:pb dup getX 1.9 sub putX !pb0
:pb dup getX p12-radius add p12-thick add 2 add putX dup getY 3.5 sub putY !pb1
:pb dup getX p12-radius add p12-thick add 2 add putX dup getY 3.5 add putY !pb2
:pt dup getX 1.9 sub putX !pt0
:pt dup getX p12-radius add p12-thick add 2 add putX dup getY 3.5 sub putY !pt1
:pt dup getX p12-radius add p12-thick add 2 add putX dup getY 3.5 add putY !pt2

```

```

:pb0 :pb1 :pb2 :pt0 :pt1 :pt2
triangle !disc_v1
:pb dup getX 1.9 add putX !pb0
:pb dup getX p12-radius sub p12-thick sub 2 sub putX dup getY 3.5 add putY !pb1
:pb dup getX p12-radius sub p12-thick sub 2 sub putX dup getY 3.5 sub putY !pb2
:pt dup getX 1.9 add putX !pt0
:pt dup getX p12-radius sub p12-thick sub 2 sub putX dup getY 3.5 add putY !pt1
:pt dup getX p12-radius sub p12-thick sub 2 sub putX dup getY 3.5 sub putY !pt2
:pb0 :pb1 :pb2 :pt0 :pt1 :pt2
triangle !disc_v2
[:disc_v1] [:disc_v2] cp-csg-difference !disc_v1
[:disc_v1 :disc_v2] flatten !disc_v

% horizontal actuator
:point dup getZ p17-offz add putZ dup getY p17-offy sub putY !p
:p dup getX size 2.0 div sub putX
:p dup getX size 2.0 div add putX
p17-radius 2.0 div
kseg
%p0, p1, radius, divisions
cylinder !actuator_h

% horizontal actuator disc
:point dup getZ p17-offz add putZ dup getY p17-offy sub p17-radius 2 mul add putY !p
:p dup getX p21-radius sub p21-thick sub clearance sub putX
:p dup getX p21-radius sub p21-thick sub clearance sub 1 sub putX
p17-radius 3 mul
kseg
%p0, p1, radius, divisions
cylinder !disc_h1
:point dup getZ p17-offz add putZ dup getY p17-offy sub p17-radius 2 mul add putY !p
:p dup getX p21-radius add p21-thick add clearance add putX
:p dup getX p21-radius add p21-thick add clearance add 1 add putX
p17-radius 3 mul
kseg
%p0, p1, radius, divisions
cylinder !disc_h2
[:disc_h1 :disc_h2] [:actuator_h] cp-csg-difference !disc_h

[
:rod_v
:actuator_v
:disc_v
:actuator_h
:disc_h
] flatten

```

planePN

```

usereg

% point normal
!normal !point

:normal cp-pl-fromnormal
:point cp-world2int cp-pl-movept

```

tube

```

usereg
isPlay.tools begin

%p0, tall, radius, thick, kseg
!kseg !thick !radius !tall !p0

:p0
:p0 dup getZ :tall add putZ
:radius :thick add
:kseg
%p0, p1, radius, divisions
cylinder !outer

:p0
:p0 dup getZ :tall add putZ
:radius
:kseg
cylinder !inner

[ :outer ] [ :inner ] cp-csg-difference
end

```

KS

```

[ (0,0,0) (1,0,0) ]
[ (0,0,0) (0,1,0) ]
[ (0,0,0) (0,0,1) ]

```

cylinder

```

usereg

%p0, p1, radius, divisions
!divisions !radius !p1 !p0

{ !v
:v (1,0,0) cross (0,0,0) eq
{ :v (0,1,0) cross (0,0,0) eq
{ :v (0,0,1) cross }
{ :v (0,1,0) cross }
ifelse
}
{ :v (1,0,0) cross }
ifelse
} !perpendicular

:p1 :p0 sub normalize !n

:n :perpendicular !yaxis
:n :yaxis cross !xaxis

[
:p0 :xaxis add :p0 :yaxis add :p0 cp-pl-register
:p1 :yaxis add :p1 :xaxis add :p1 cp-pl-register
0 360.0 :divisions div 360.0
{
!alpha
:xaxis :n :alpha rot_vec normalize :radius mul !x

```

```

: yaxis :n :alpha rot_vec normalize :radius mul !y
: p0 :y add :x add
: p0 :y add :n add
: p0 :y add
cp-pl-register
} forx
] cp-po-register

```

block

```

usereg
isPlay.tools begin
!pt3 !pt2 !pt1 !pt0
!pb3 !pb2 !pb1 !pb0

[
% Seitenflächen
:pb0 :pb1 :pt0 cp-pl-register
:pb1 :pb2 :pt1 cp-pl-register
:pb2 :pb3 :pt2 cp-pl-register
:pb3 :pb0 :pt3 cp-pl-register
%Boden, Deckel
:pb0 :pb3 :pb2 cp-pl-register
:pt2 :pt3 :pt0 cp-pl-register
] cp-po-register
end

```

star08

```

usereg
isPlay.tools begin

% point, dist, radius, width, height, offturn, count

!count !offturn
!height !width !radius !dist !point

%Block:
(1,0,0) :dist mul :width 2.0 div (0,-1,0) mul add !pb0
:pb0 (1,0,0) :radius mul add !pb1
:pb1 (0,1,0) :width mul add !pb2
:pb2 (-1,0,0) :radius mul add !pb3

[ :pb0 :pb1 :pb2 :pb3 ]
{ dup getZ :height abs add putZ } map
aload !pt3 !pt2 !pt1 !pt0

%um offturn drehen
[ :pb0 :pb1 :pb2 :pb3 :pt0 :pt1 :pt2 :pt3 ]
{ (0,0,1) :offturn rot_vec } forall
!pt3 !pt2 !pt1 !pt0 !pb3 !pb2 !pb1 !pb0

[
[:pb0 :pb1 :pb2 :pb3 :pt0 :pt1 :pt2 :pt3 ]
{ :point add } forall
block

%im Kreis kopieren
:count 1 sub {
[ :pb0 :pb1 :pb2 :pb3 :pt0 :pt1 :pt2 :pt3 ]
{ (0,0,1) 360.0 :count div rot_vec } forall
!pt3 !pt2 !pt1 !pt0 !pb3 !pb2 !pb1 !pb0

[ :pb0 :pb1 :pb2 :pb3 :pt0 :pt1 :pt2 :pt3 ]
{ :point add } forall
block
} repeat
]
end

```

tooth

```

usereg
isPlay.tools begin
% point height radius thick deg_start deg_end
% inclin kseg
!kseg !inclin !deg_end !deg_start !thick !radius
!height !point

[ ] !tooth1
:deg_end :kseg sub :kseg neg :deg_start {

```

```

!counter
[
(0,0,0) :radius putX !p
:p (0,0,1) :counter rot_vec :point add !pb0
:p dup getX:thick add putX (0,0,1) :counter rot_vec
:point add !pb1
:p (0,0,1) :counter :kseg add rot_vec :point add !pb2
:p dup getX :thick add putX (0,0,1) :counter
:kseg add rot_vec :point add !pb2

(0,0,0) :radius putX :height putZ !p
:p (0,0,1) :counter :kseg add rot_vec :point add !pt3
:p dup getX :thick add putX (0,0,1) :counter
:kseg add rot_vec :point add !pt2
% increase height for inclination
:height :inclin 0.65 mul :kseg mul add !height
(0,0,0) :radius putX :height putZ !p
:p (0,0,1) :counter rot_vec :point add !pt0
:p dup getX:thick add putX (0,0,1) :counter rot_vec
:point add !pt1
:height :inclin 0.35 mul :kseg mul add !height
:height 0 lt {
:pt0 !temp
:pb0 !pt0
:temp !pb0
:pt1 !temp
:pb1 !pt1
:temp !pb1
:pt2 !temp
:pb2 !pt2
:temp !pb2
:pt3 !temp
:pb3 !pt3
:temp !pb3
} if
:pb0 :pb1 :pb2 :pb3 :pt0 :pt1 :pt2 :pt3
block :tooth1 ] flatten !tooth1
} for

:tooth1
end

```

simpleBlock

```

usereg
isPlay.tools begin
% point, size_x, size_y, size_z

!size_z !size_y !size_x !point

:point dup getX :size_x 2.0 div sub putX
dup getY :size_y 2.0 div sub putY !pb0
:pb0 dup getX :size_x add putX !pb1
:pb1 dup getY :size_y add putY !pb2
:pb0 dup getY :size_y add putY !pb3

:pb0 dup getZ :size_z add putZ !pt0
:pb1 dup getZ :size_z add putZ !pt1
:pb2 dup getZ :size_z add putZ !pt2
:pb3 dup getZ :size_z add putZ !pt3

:pb0 :pb1 :pb2 :pb3 :pt0 :pt1 :pt2 :pt3 block
end

```

triangle

```

usereg
isPlay.tools begin
!pt2 !pt1 !pt0
!pb2 !pb1 !pb0

[
% side faces
:pb0 :pb1 :pt0 cp-pl-register
:pb1 :pb2 :pt1 cp-pl-register
:pb2 :pb0 :pt2 cp-pl-register
% bottom face, top face
:pb0 :pb2 :pb1 cp-pl-register
:pt1 :pt2 :pt0 cp-pl-register
] cp-po-register
end

```


testCylinder

```

applet-clear deleteallmacros usereg
clear
isPlay.tools.begin
KS

(0,0,0) (1,0,0) 1.0 10
%p0, p1, radius, divisions
cylinder
!cyl1

(0,0,0) (1,0,1) 1.0 10
%p0, p1, radius, divisions
cylinder
!cyl2

%[:cyl1] [ :cyl2 ] cp-csg-difference
%dup :cyl2 append

[ :cyl2 ] [ :cyl1 ] cp-csg-difference
dup :cyl1 append

%{ -0.01 isPlay.tools.shrink-cp } forall
{ cp-po-render } forall
end

```

testTube

```

applet-clear deleteallmacros usereg
clear

%p0, p1, radius, thick, kseg
(0,0,0) 3 1 0.1 25
isPlay.tools.tube !tubel

:tubel
{ /stdRed (0,0,0) 0 0 1 cp-po-setproperties }
forall

```

testBlock

```

applet-clear deleteallmacros
clear
isPlay.tools.KS

(0,0,0) (1,0,0) (1,1,0) (0,1,0)
(0,0,2) (1,0,2) (1,1,2) (0,1,2)
isPlay.tools.block
cp-po-render

```

testStar08

```

applet-clear deleteallmacros
clear

```

```
isPlay.tools.KS
```

```

% point, dist, radius, width, height, offturn, count
(1,1,1) 2 .2 1 1 90 6
isPlay.tools.star08

{ cp-po-render } forall

```

testTooth

```

applet-clear deleteallmacros usereg
clear

/stdRed (0,0,0) 0 0 0 cp-setproperties

(0,0,0) 0.00001 4 2 0 360 .04 5
% point height radius thick deg_start
% deg_end inclin kseg
isPlay.tools.tooth !tooth1

(10,0,0) 3 4 2 45 90 .05 .2
% point height radius thick deg_start
% deg_end inclin kseg
isPlay.tools.tooth !tooth2

% poly, count
%:tooth1 3 isPlay.tools.circularCopy !tooth1

:tooth1 { cp-po-render } forall
:tooth2 { cp-po-render } forall

```

testSimpleBlock

```

applet-clear deleteallmacros
clear
isPlay.tools.KS

(1,0,1)
1
1
2
isPlay.tools.simpleBlock
cp-po-render

```

testTriangle

```

applet-clear deleteallmacros
clear
isPlay.tools.KS

(0,0,0) (1,-1,0) (1,1,0)
(0,0,1) (1,-1,1) (1,1,1)
isPlay.tools.triangle
cp-po-render

```

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