Numerically Controlled Pen Plotters in Art

Building an Experimental Pen Plotter Allowing for Additional Creative Possibilities

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ABSTRACT

This research aims at exploring the potential to extend the creative capabilities of a pen plotter. While commercial pen plotters offer limited possibilities for controlling a pen’s pressure or its height in relation to the drawing surface, developing an advanced pen-lift mechanism would allow for dynamically controlling the height of a writing or drawing implement with adequate resolution. These improvements permit using an ink brush or pen with a flexible tip to modulate the stroke weight of the drawn lines.

Designing and building additions and advancements to an experimental pen plotter based on a laser engraving machine allows for practical experimentation, resulting in drawings aiding in validating the claimed improvements. In addition, a theoretical look, based on literature and expert interviews, provides insight to pen plotters, their operation and use, their history, their significance in algorithmic art, and their current revival reflected in an active community.

The experimentation with the improved pen plotter resulted in ten drawings which illustrate the gained potential as a creative tool. Some of which are based on algorithms generating lines with varying stroke weights. Others are halftone images based on photographs and drawn as lines with dynamically changing thickness.

A recent revival, especially in generative art and design, can be observed despite pen plotters having long been replaced by other hard copy devices. This research might encourage other pen plotter community members, which are often driven by innovation while generously sharing their knowledge, to pursue similar experiments.

Keywords: Pen Plotter, Drawing Machine, Pen-lift Mechanism, Algorithmic Art, Generative Art, Computer Art

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GLOSSARY

Accuracy

The more accurate a pen plotter is, the closer the dots and, consequently, the closer the dimension of lines are to their desired value and position. The accuracy is essential to produce drawings that are in scale. The accuracy of a plot largely depends on the drawing surface and its property to change in size depending on air humidity and temperature (Hall 22). ISO defines accuracy as the product of precision and trueness (International Organization for Standardization, Accuracy of measurement methods and results — Part 1: General principles and definitions).

Additive manufacturing

3D printing is a typical additive manufacturing method where plastics or metals are joined together to form a workpiece. This may be achieved by gradually adding molten material to the workpiece. Additive manufacturing is opposed to subtractive manufacturing, where material is cut away from a workpiece, typically by milling, drilling, and turning, to alter its shape.

Arduino

A combination of hardware boards containing a microcontroller and specific software to programme the boards, as the co-founder of the Arduino project explains (Banzi 17).

Array

In computer science, an array is a collection or list of elements, such as objects or values. For example, the colour information of pixels in raster images can be stored in arrays.

CAD

Acronym for Computer-Aided Design describing a design method utilising suitable computer systems (Greulich 149-150). CAD can be done in two or three dimensions.

CAM

Acronym for Computer-Aided Manufacturing, describing the programming process, namely, the generation of control code for CNC machines. While this was traditionally done by a person, nowadays, CAD and CAM software are often integrated into one package, whereas CAM, generating G-code, relies on data generated by the CAD process.

CNC

Acronym for Computer Numerical Control, which describes the automated control of manufacturing machines. CNC based manufacturing includes drilling, milling, plasma cutting, turning, and 3D printing, which generally are controlled by G-code. Early examples of numerical control can be found in the automated looms of the 19th century, where punch cards contained the control code for the machines. Also, pen plotters are numerically controlled.

DC-motor

A DC-motor is an electric motor powered by a direct current. Changing the voltage of its power supply affects the motor’s speed.

Dot gain

The tendency of a dot of ink to grow in size after being applied onto the drawing surface while it is absorbing into the medium.

Drawing medium

The surface on which ink or dye is transferred during the drawing process. These are mostly paper, transparency or polyester film (Hewlett-Packard, *HP 7475A*). However, experimental pen plotters can draw on several surfaces such as eggs or walls.

Drawing utensil

The means by which ink, pigment etc., is applied to the drawing surface. These are typically felt-tip or ballpoint pens and nibs or pencils in pen plotters.

FFF

Acronym for Fused Filament Fabrication, which is a 3D printing method where the molten plastic filament is fused together in order to form a workpiece. FFF printers are depositing the material in stacked layers, whereas the molten filament adheres to the previous layer.

Fortran

Programming language for scientific and technical purposes developed in the 1950s at IBM (Greulich 364).

G-code

Programming language used in CNC manufacturing and contains instructions for numerically controlled machines. G-code is interpreted in the controller of a CNC machine, which then controls the output to the motors and servos in order to execute the physical movements. While modern pen plotters are typically controlled using HP-GL, G-code has become a popular choice for controlling experimental pen plotter builds due to its easy implementation in controllers.

Gantry

In the case of pen plotters and other robots, a gantry is a bridge-like, sometimes mobile, structure that carries a pen or tool carriage that can run along its side.

Halftone

A technique to convert an image with smooth progressions of tones, which is called a continuous tone image, into patterns of solid dots to enable reproduction using a conventional printing press (Campbell 153). In pen plotting, halftoning is used for reproducing continuous tone images while circumventing the limitations of drawing with the constant stroke weight of a pen.

Hardcopy device

A hardcopy device is a computer peripheral used to reproduce digital data, such as text or graphics, onto paper. Today, ink-jet and laser printers are the most common hardcopy devices, while pen plotters are also considered as such.

HP-GL

Hewlett-Packard Graphics Language is a control language developed for pen plotters and the de facto standard to control professional pen plotters. HP-GL relies heavily on the firmware of a device, which makes it possible, for example, to plot text with a few simple commands.

IDE

Acronym for the Integrated Development Environment. A combination of the tools needed for software development integrated into one user interface (Greulich 460-461).

Pen carriage

In a pen plotter, the pen carriage carries the pen-lift mechanism. The pen carriage often runs alongside a gantry, spanning horizontally over the drawing surface.

Precision

The precision of a pen plotter is the quality defining how close two dots effectively can be drawn together when they should share the same position. Precision becomes visible when, for example, two lines originate from the same point (International Organization for Standardization, Accuracy of measurement methods and results — Part 1: General principles and definitions).

Repeatability

A pen plotter controlled with high repeatability can repeatedly return to the same point over time, independent of the direction from which the movement originates or possibly changing pens. Repeatability is, e.g. important to draw circles with start and endpoints close together or draw lines originating from the same point.

Resolution

The resolution of a pen plotter defines the amounts of increments with which its movements can be controlled and results in the shortest possible distance between two points. For example, a low resolution becomes visible when stair steps appear in a circle drawn by a plotter (Hall 2). The resolution with which a plotter can effectively draw depends on its firmware and its electromechanical components.

Servo

A servo motor is an electric motor used to make controlled movements. Servo motors are equipped with a device providing information about their position. Servos are commonly used in pen plotters and other hardcopy devices.

Solenoid

A solenoid is an electrically activated linear actuator with a movable core and an electric coil. Simple designs allow the core to move to either of two positions, while more advanced voice coil solenoids can be controlled with more resolution. In commercial pen plotters, solenoids are the most common means to activate the pen-lift mechanism.

Stepper motor

A stepper motor is an electric motor that can move in small and precise increments. Stepper motors allow a pen plotter to make controlled movements.

SVG

Acronym for Scalable Vector Graphics, allowing to save two-dimensional vector graphics. This format is commonly used as an input format to generate control code for pen plotters.

Vector graphics

Vector graphics are graphics defined as geometry within a coordinate system, as opposed to pixels in raster graphics. Vector graphics can be scaled without losing quality. Pen plotters produce vector graphics, i.e. they draw lines based on coordinates.

1 INTRODUCTION

In recent years, pen plotters have regained popularity as an artistic tool. Enthusiasts buy new plotters designed for the current market, acquire vintage commercial plotters or build their own. All commercial plotters have a pen lift mechanism that allows the pen to be either on or above the paper resulting in the ability to draw precise lines with a constant weight. While drawings with consistent line weights were desirable in architectural and mechanical technical drawings, this feature limits the creative possibilities. Precise and dynamic control of the pen height, on the other hand, would allow influencing the stroke weight when using a brush pen or another drawing implement with a conical tip.

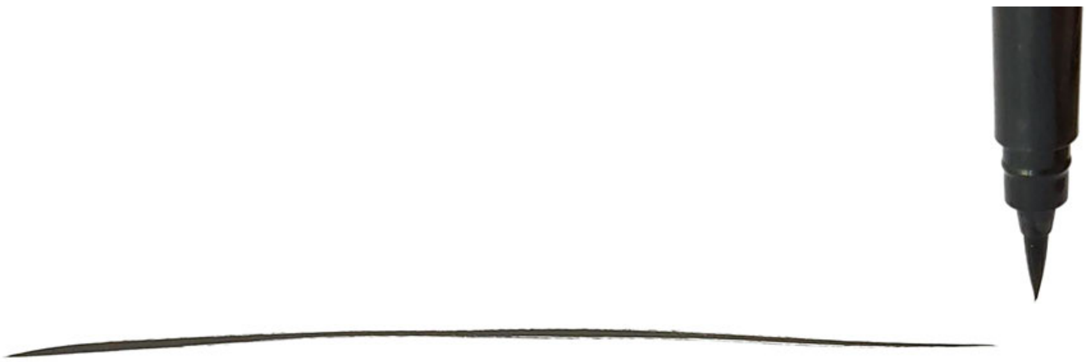


Fig. 1. The variable line weight results from controlling the height of a Pentel Pocket Brush Pen in relation to the paper's surface.

Most of today's devices have become black boxes, with their inner workings hidden from the user. As a result, their function has become inconceivable: A click on the printer icon ideally initiates a blank piece of paper being pulled into a device to re-appear as a hardcopy of the desired information shortly after. Thus, the transformation from paper to print-out, the actual application of dye or ink, stays obscured from our eyes. In comparison, pen plotters are very transparent, allowing users to observe how the output is drawn, line by line. Furthermore, the swift and precise movements of the pen, gliding over the paper, are mesmerising and combine into a choreography that is satisfying to watch.

Pen plotters were replaced as office appliances with faster, more dependable hard copy devices during the nineties. However, despite being widely obsolete, their characteristics led to a revival as valued instruments for artists in algorithmic art. While plotting artwork, an alluring contrast between the perfect precision of digitally defined lines and the analogue quality resulting from the interaction between pen, ink, and paper, emerges.

Designers and artists made previous attempts to gain the ability to control the pen height in plotters precisely. However, hard- and software requirements have to be met to succeed. The former requirements include mechanical issues, such as the plotter's frame and pen-lift mechanism's stiffness and rigidity and the electromechanical means to control and drive the pen-lift mechanism. The latter requirements concern the firmware of the plotter's controller, the control language, which needs to include commands to dynamically control the height of the pen, and software that can generate the instructions in the control language depending on the desired line weights or dot sizes.

While vintage plotters are still very reliable, 40 years after they were initially produced, they cannot be modified easily as a consequence of their cost-effective and compact design in addition to their closed source firmware. On the other hand, new commercial pen plotters often run with very well documented open-source software, allowing for changes and additions. However, their mechanical design does not guarantee a constant height of the pen carriage over the drawing surface (Oskay, *1 Apr. 2022*). In conclusion, building a pen plotter based on a suitable design remains the most viable option to gain the ability to experiment with alternative hard- and software solutions, especially when adding excessive weight to the pen carriage is essential.

In this research, I build an experimental pen plotter that allows for additional creative possibilities compared to plotters currently used in the domain of generative art and design. Namely, I design and manufacture a mechanism that allows setting the position of a drawing utensil in relation to the drawing surface to gain the ability to control the width of a drawn line. In addition to developing and prototyping the required hardware, I write the necessary software that generates the control code to operate the plotter.

After designing and developing the pen plotter, experiments with the resulting hard- and software should confirm that controlling the pen height dynamically and precisely allows for additional creative possibilities. The development process and the utilisation of this experimental pen plotter are documented. The resulting plots serve to verify the newly gained possibilities.

In the first part of this paper, I describe the different plotter designs and their operation. Then I overview the pen plotter history and significance of pen plotters, especially for algorithmic art and design. Furthermore, I look at different traditional drawing techniques compared to the abilities of commercial pen plotters. This theoretical part will be based on book studies and expert interviews.

During this research, I collected and tested commercial pen plotters and other technical drawing implements, which helped me understand their technology, usage, and limitations. Furthermore, I have become a member of the pen plotter community and advanced from being an observer to a contributor to specific topics, actively exchanging my thoughts and experiences.

Looking back at my education and career choices over the past 28 years, one thing, in particular, stands out: I constantly moved in between the fields of technology, art, and design. I am a certified electrician holding a degree in Media Arts who has been teaching designers for close to a decade and am currently working in design engineering while finishing my studies in Audiovisual Media Culture. Having engineering knowledge allows applying technology to the creative field. Similarly, artistic work is a welcome excuse to experiment with technology in ways they were not intended. I am content that I can satisfy my creative traits and appreciation for technology in this research. In addition, I hope to successfully convey my fascination for pen plotters to the reader of this text.

2 PEN PLOTTER

The development of numerically controlled pen plotters started in the 1950s. Initially, these machines were only used in specialised applications and were very high in cost. However, subsequent advancements in technology made them more convenient and affordable for a broader user group. During their heyday in the 1980s, pen plotters were available in different sizes and shapes, serving various purposes until they were gradually replaced in the following decade. As a result, pen plotters lost their economic significance and were deemed obsolete. Nonetheless, a recent revival made pen plotters a thought-after tool for generative artists, designers, and other technology enthusiasts. A growing online community around pen plotters is a testament to this new spike of interest in and fascination with these computerised drawing machines.

2.1 Definition

Plotters are output devices that reproduce graphics and texts by transferring ink or dye onto a drawing surface. There are two broad categories of plotters, pen plotters utilising pens and electrostatic plotters comparable to laser printers (Greulich 715). Pen plotters are based on vectors, while electrostatic plotters are based on rasters (Hall 1). The following text focuses on pen plotters, excluding electrostatic plotters and other pixel-based printing systems like large format inkjet printers, colloquially called plotters. The term plotter originates from the verb plot: "to make a map or diagram of, lay down on paper according to scale;" and "to lay plans for, conspire to effect or bring about" ("plot (v.)"). Alternatively to the term pen plotter, the terms drawing machine, drawbot and drawing table are also used depending on their size and construction.

2.2 Classification

Pen plotters can be configured as different types, depending on their purpose, drawing utensils, drawing surfaces and the available space. The most common types in a production setting were drum plotters, micro-grip plotters and flatbed plotters. In addition, there were many plotters developed to serve a particular niche and plotters of an experimental nature.

Drum plotters

The paper is mounted to or hanging over the drum of a drum plotter, serving as the drawing surface's base. The paper moves on the X-axis, while the pen carriage moves on the Y-axis. Drum plotters are allowed to plot on a comparably big area, considering their small footprint, which is why they were popular in design offices.

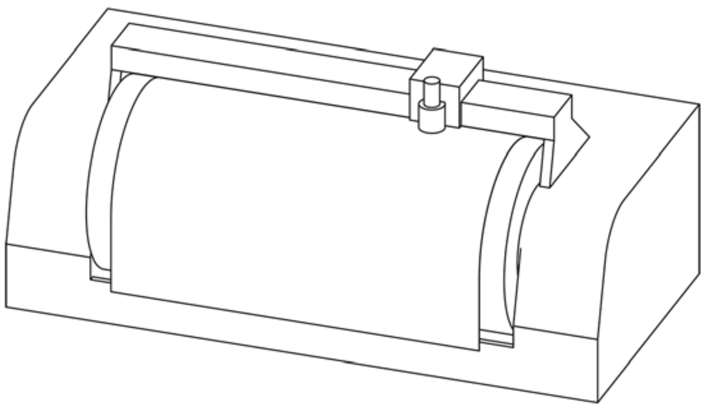


Fig. 2. Illustration of drum plotter.

Micro-grip plotters

Micro-grip plotters pinch the plotting medium between pinch and grit wheels on both sides of the Y-axis, along which the pen carriage is moving. The plotting medium is sliding in the X-axis over a platen serving as the base of the drawing surface. These plotters are available as desktop versions for plots up to DIN A3 format or large-format versions, which share the same advantages and popularity as bigger drum plotters concerning their footprint.

Fig. 3. HP7475A desktop plotter with detail of the micro-grip drive for paper movement.

Flatbed plotters

Flatbed plotters are designed so that the plotting medium is mounted onto a flat stationary surface while a gantry carrying the mechanism for the Y-axis is moving on the X-axis. In these plotters, the footprint is proportional to the size of the maximum available plotting area. In addition, some flatbed plotters can be set up at an angle or in an upright position, reducing the required footprint.

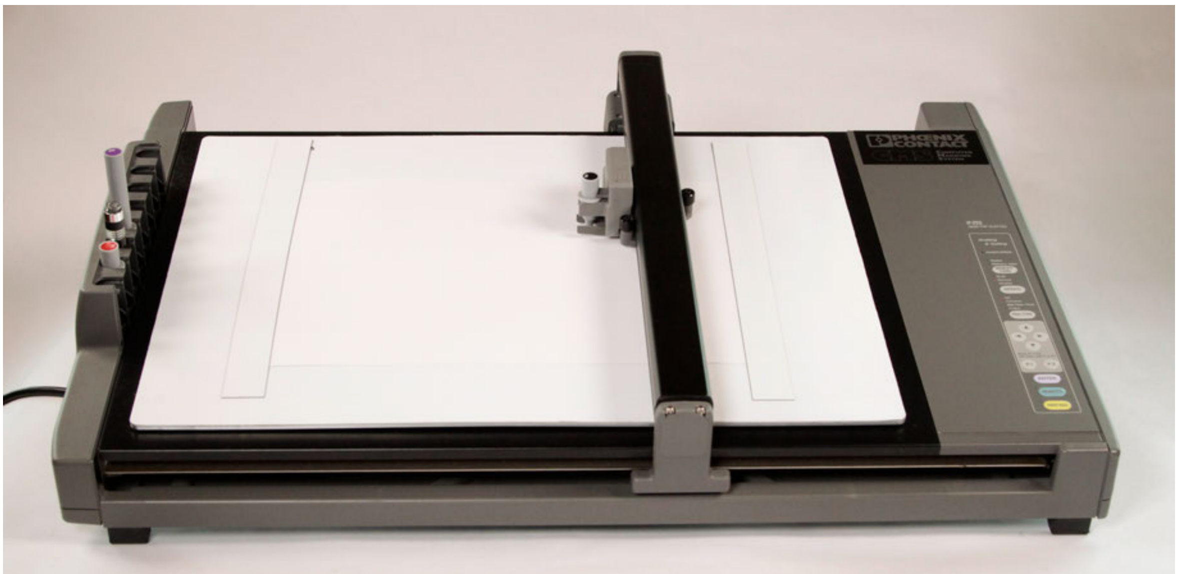


Fig. 4. Re-branded Mutoh IP-220 flatbed plotter with movable gantry.

Portal plotters

Portal plotters are related to flatbed plotters in their design, with the difference that the gantry is stationary and the drawing surface is moving on the X-axis underneath. This design simplifies the driving mechanism for the pen carriage. However, the movable drawing surface almost doubles the necessary footprint.

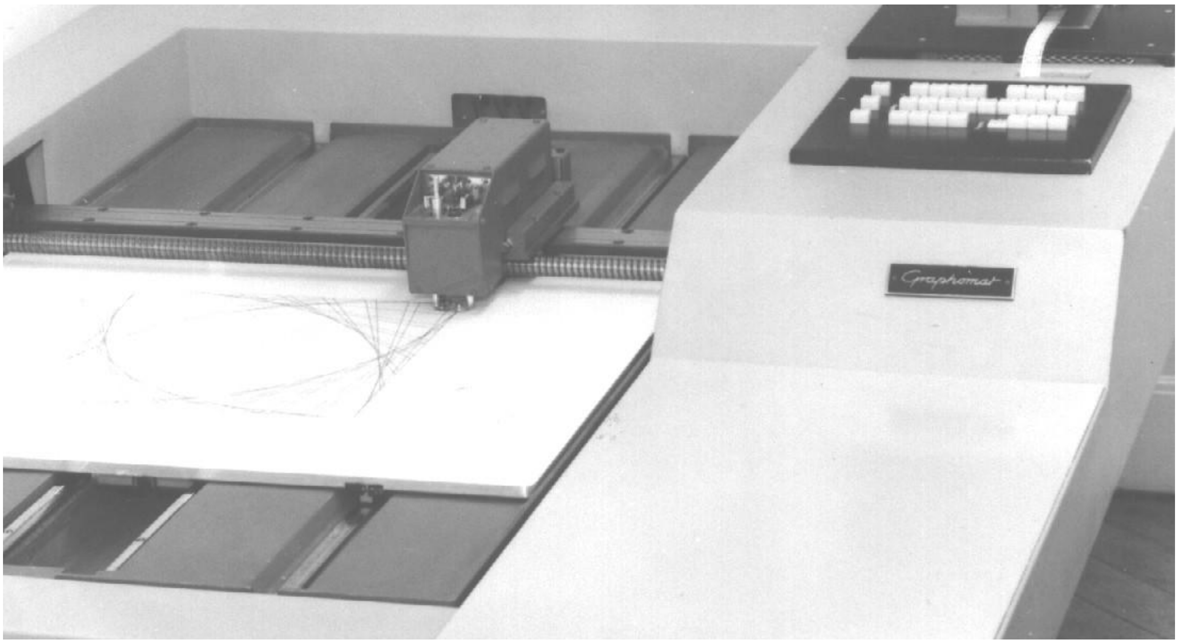


Fig. 5. ZUSE Graphomat Z64-G1 with fixed gantry and movable table.

Scribers

Scribers are compact and mobile pen plotters which can be placed on drawing surfaces, such as blueprints, to add text labels and symbols to an existing drawing. They are always equipped with a keyboard, allowing the user to enter the text to be plotted, while most feature an additional display. Before use, a drafting pen in the corresponding size for the desired character height has to be attached to the drawing arm. Scribers have been surprisingly popular, making the tedious task of writing labels much quicker and less error-prone.

Fig. 6. Rotring CS-50 Scriber with detail of pen-lift mechanism.

Contemporary pen plotters for handwriting-like applications

Pen plotters are still offered for handwriting-like applications such as addressing envelopes for marketing purposes, for signing diplomas or autographs. The most prominent company offering Signature and handwriting machines is Damilic, with their Autopen line of signature and handwriting machines (Edman, *13 Jan. 2022*). These devices feature a writing arm equipped with a unique pen holder, allowing to secure a fountain pen or other writing implement at an angle.

Contemporary plotters marketed at artists

During the pen plotters' revival, some manufacturers began to offer plotters and plotter kits mainly marketed toward artists. Most are horizontal T-bot gantry plotters (Oskay, *21 Nov. 2021*), consisting of two beams arranged as a cross. The X- and Y-axis are driven by stepper motors, while a hobby servo operates the pen-lift mechanism. These plotters are available in different sizes with a plottable area of up to DIN A1 format.

Experimental and DIY plotters

Pen plotters are prevalent subjects in the maker scene. According to Lenore Edman, co-founder of Evil Mad Scientist Laboratories, building DIY plotters are low barrier entry projects due to the availability and low costs of needed materials while offering educational value about design, digital fabrication, and art (Edman, *13 Dec. 2021*). Experimental plotters have been built in numerous shapes and sizes and can plot onto various materials. Popular designs are BrachioGraph, V-Plotter, EggBot, Open Source Turtle Robot, and Omni wheel plotter, to name a few.

2.3 Operation

Typically, a pen plotter moves a drawing utensil over a drawing surface while the tip of the drawing utensil is either raised off or in contact with the surface, resulting in the transfer of ink or dye onto the surface. The two commands for these operations are commonly “pen up” and “pen down”. More advanced pen plotters have a setting for the so-called pen force, with which the drawing utensil is pressed onto the surface. For example, for a pen plotter to draw a line from point P1 to point P2, it moves with the elevated pen to P1, lowers the pen and moves to P2. If the line should continue from point P2, the pen continues moving; otherwise, it is lifted. Usually, the position of the points is defined as cartesian coordinates.

Most commercial plotters use DC motors equipped with optical encoders for positioning pen and paper. The encoders give feedback about the motors’ position and direction to the control electronics (Wilson and Johnson 26). The accurate feedback allows coordinating the speed in X and Y directions resulting in a movement along the correct vector. However, some early plotters used stepper motors (Johnson) operating with a low resolution leading to undesirable artefacts in their output when drawing oblique lines. Other drawing machines were controlled by a combination of highly precise planetary gearboxes (Zuse, *Zuse Computer* 74), resulting in the ability to draw slanting lines without artefacts. However, with the advancement of technologies, it became possible to achieve sufficient resolution even when using stepper motors. Another interesting method to drive a plotter is the linear stepper motor, where the stator is alongside the drawing area (Tsai and Ciardella).

The pen-lift mechanism is another essential part of a plotter. It is usually operated by a solenoid that can either be fully extended or contracted, resulting in the pen's location above or on the paper. Alternatively, voice coils, also allowing control of the pen's pressure on the drawing surface, are used in more advanced devices (Haselby et al. 26-27). While solenoids are comparably heavy, they are usually not mounted directly on the pen carriage but linked to it mechanically. On the other hand, voice coils are lighter, allowing them to be directly mounted on the pen carriage and lift the pen holder via a pen lift arm. A third typical method to lift the pen of a plotter is achieved with servos. Especially in pen plotter kits and plotters offered to artists, hobby servos, commonly found in radio controlled toys, are directly mounted on the pen carriage.

The pens offered for commercial plotters are typically fibre-tip pens, roller-ball pens and technical drafting pens in disposable and refillable variants (Hewlett-Packard, *Supplies Source* 6-9). In addition, the Japanese manufacturer Mutoh was selling plotter pencils that can advance the leads automatically every time the pencil is lifted (Niemeyer) and developed a corresponding mechanism to automatically feed the pencil with spare leads (Tanaka). Advanced plotters allow using several pens, which can plot in multiple colours and multiple line weights. The pens are either stored in a pen carousel or alongside the plotting area, where they can be parked and picked up by the pen carriage. When a pen is parked, it is automatically capped to prevent it from drying out.

A condition for producing successful plots is that the paper, film or vellum has to remain tight against the plotter's bed, drum or platen, preventing buckling. In smaller drum plotters, this is achieved with pinch wheels pressing the plotting medium against the drum, mechanisms clamping it to the drum, or utilising sticky tape. The pinch wheel design can be combined with a vacuum in micro-grip plotters, drawing the plotting medium to the platen (Kaplan and Townsend 34-36). In addition, flatbed plotters often feature an electrostatic paper hold-down where the plotting medium is clinging to the bed due to its static charge. This method is more convenient than holding the plotting medium with magnetic strips, with which the pen might collide (Hart, *Big Draws* 264).

Commercial pen plotters are controlled by a language with a plotter specific instruction set. The most common control language is Hewlett-Packard Graphics Language, HP-GL, developed by Hewlett and Packard. Besides instructions for defining the plotting area and scaling, the most used instructions allow selecting a pen from the magazine, controlling pen up/pen down movements, and plotting a line to a point, absolute or relative to the current pen position. In addition, HP-GL features instructions to plot circles and even texts in different fonts (Hewlett-Packard, *HP 7470A*). These instructions are usually transmitted from the host computer to the plotter via a serial connection, where they are interpreted and executed. HP-GL is still used in some cutting plotters offered on today's market. Furthermore, other plotter control languages, such as Roland's CAMM-GL (Roland Digital Group), are heavily based on HP-GL. Early pen plotters, as well as some plotters marketed today, are controlled by proprietary languages.

2.4 History

Various mechanical drawing machines, apparatuses, and instruments were used in engineering, science, and entertainment, long before the age of digital computers and numerically controlled pen plotters. Many of them were relatively simple in their design, such as the pantograph for scaling drawings or the ellipsograph used to draw ellipses. In contrast, others were more complex, for which the perspectograph, used in photographic surveying, serves as a good example. Also, drawing toys like the Etch-a-Sketch and the spirograph, which still find their way into the hands of today's children, have to be mentioned. Even though very different in their appearance, the 18th-century automata, built by Pierre Jaquet-Droz and his son Henri-Louis are more closely related to modern pen plotters. Namely, the writer, built by Pierre and the draughtsman, built by his son, were representations of small boys sitting at a table capable of writing and drawing, respectively (MahN, *Automate ‘L'Ecrivain’*; MahN, *Automate ‘Le Dessinateur’*). The movements of their arms and hands were controlled by cams that could either be programmed or interchanged. Their automata are considered early computers and were so advanced for their time that the Spanish Inquisition temporarily imprisoned the father and his automaton under the accusation of blasphemy (Wood xiv).

Fig. 7. The draughtsman by Jaquet-Droz, drawing a portrait of King Georges III.

In 1959 the first electromechanical plotters were introduced to the market by the American companies Benson and CalComp (Gerulat 291). The plotter of the latter company was a small format 12” sprocket feed roll-paper-plotter (Hall 16), driven by stepper motors, which, at that time, could not be controlled in a matter, that would have allowed drawing oblique lines without artefacts.

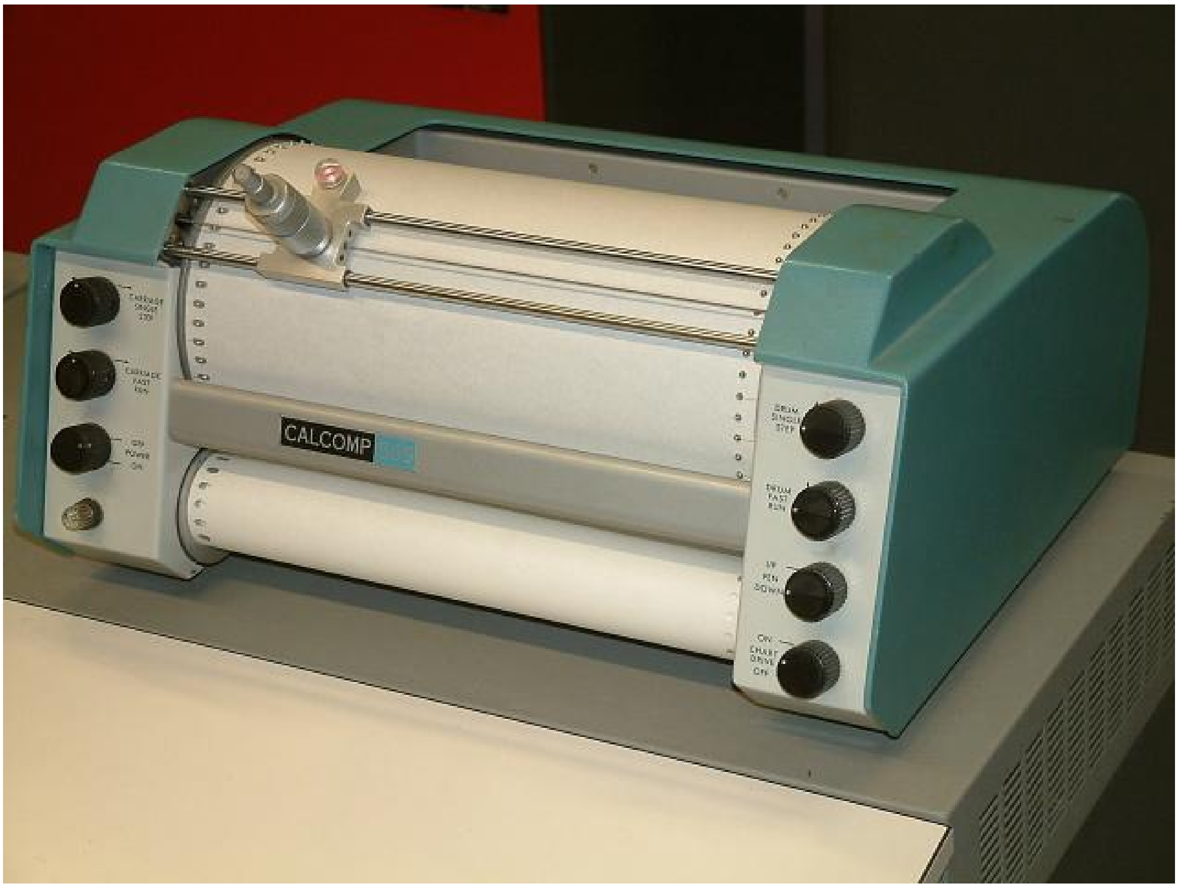


Fig. 8. The CalComp 565 was an early pen plotter.

Meanwhile, in Europe, the German companies Aristo and Zuse KG (Mathes; Zuse, *Konrad Zuses Werk* 104), the Norwegian company Kongsberg Våpenvabrikk AS (Haug-Hanssen 29), and the Swiss company Contraves AG (Bruderer, *Discovery of Two Historical Computers in Switzerland*) have been working on the development on much more precise numerically controlled drawing machines. While there was a cooperation between Aristo and Kongsberg Våpenvabrikk AS and later with Zuse KG, the three companies marketed their plotters eventually under their own name (Haug-Hanssen 30; Mathes 11). Zuse's Graphomat was introduced in 1961, and Aristo's Aristomat with the Essi control, developed in Kongsberg, was introduced in 1962. Similarly, Contraves' Coragraph was operational in 1963 and based on the Koordinatograf from the Swiss Haag-Streit AG (Bruderer, *Discovery of Two Historical Computers in Switzerland*; Bruderer, *18 Apr. 2022*). Kongsberg's plotters were later marketed under Kingmatic (Haug-Hanssen 8).

Kongsberg's Essi control was developed based on their experience with numerically controlled lathes. It emerged from the need to test the programs beforehand to detect mistakes, which could cause crashes between the tool and the workpiece of the machine. As a result, they constructed a machine drawing the toolpaths on paper beforehand (Mathes 8-9). Aristo and Contraves, on the other hand, developed their machines based on machines used in cartography and Zuse based on a machine used in land consolidation.

Due to their high precision, many European plotters were sold to the new continent and were used in, and arguably accelerating, the development of integrated circuits in the U.S. (Mathes 5; Haug-Hanssen 32). They were all designed as flatbed plotters and had a work surface of up to 3000 mm x 4000 mm in the case of the Aristomat (Mathes 10) or 2 x 6 m in the case of the Kingmatic in 1972 (Haug-Hanssen 39). In addition, these early European plotters were all controlled by punched paper tape.

Fig. 9. KV Kingmatic 2637. A very large flatbed plotter from 1967.

During the 1970s and especially in the 1980s, the development of pen plotters was progressing fast and promoted many innovations that later influenced other output hardcopy devices such as inkjet and laser printers. The micro-grip design by Hewlett-Packard allowed for accurate plotters to be produced more cost-effectively, which made them affordable to more customers (Jason, *19 Apr. 2022*). Pen plotters were eventually available with such amenities as an automatic sheet feeder, picking up paper from a cassette and an automatic pen changer, allowing to draw with up to eight different pens. The plotting speed increased, and accelerations up to 6g were possible (HP Computer Museum, *7550*). In addition, the control language driving the plotters was standardised, making it easier for software developers to offer interfaces to many plotter models. In the 80s and 90s of the last century, the American company Hewlett-Packard dominated the plotter market. After HP's exit from the plotter market, the Japanese companies Roland and Mutoh could increase their share while still producing pen plotters (Jason, 19 Apr. 2022).

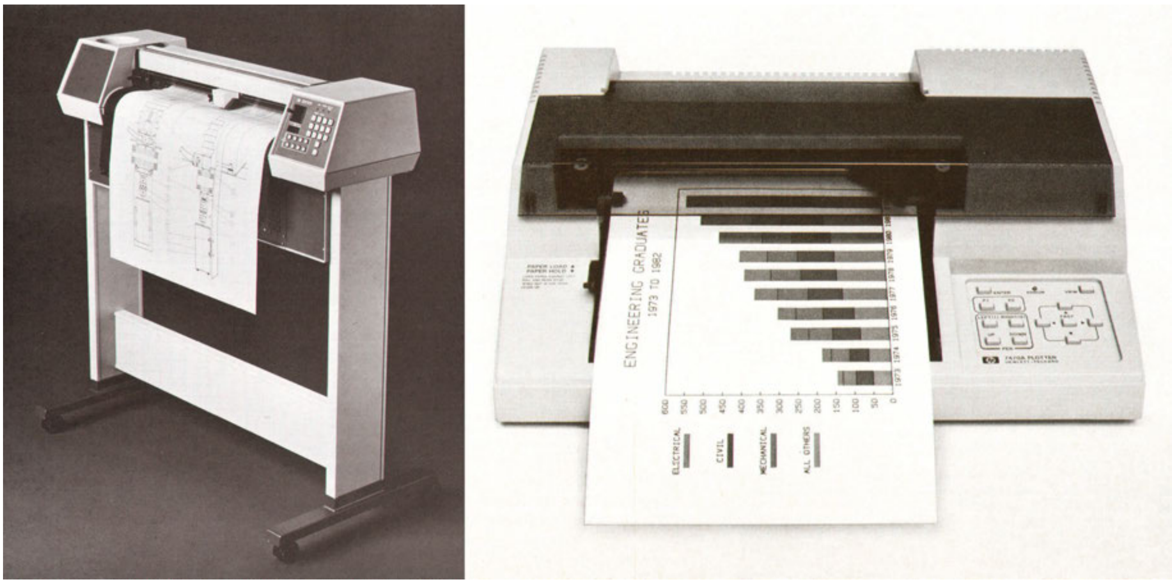


Fig. 10. Two of Hewlett-Packard's micro-grip pen plotters: The models 7580A from 1981 and 7470A from 1982.

In the 1990s, pen plotters were substituted by faster and more convenient electrostatic plotters, laser, and inkjet printers. However, some pen plotter manufacturers like Roland and Mutoh continued to produce vinyl cutting plotters, which are very similar to pen plotters in their construction. Cutting plotters have increased in popularity due to affordable models designed for arts and crafts. Nowadays, there are only a few manufacturers producing pen plotters left. Their machines are targeted at niche markets such as generative art, handwriting-like applications (Edman, *13 Jan. 2022*), and labelling purposes (Murrplastik, *Plotter systems*).

A glance over the online plotter community shows that its members are either using vintage surplus machines from the heyday of pen plotters, plotters based on self-assembled kits, DIY plotters or the AxiDraw offered by the Californian company Evil Mad Scientist. AxiDraw was introduced in 2016 as a machine allowing to write with various writing and drawing implements (Oskay, *Introducing the AxiDraw*) and has a big fanbase in generative art. Lenore Edman, the co-founder of Evil Mad Scientist, believes that the success of AxiDraw is based on the integration of hard and software, leading to a polished user experience. Also, their software is open-source, allowing artists to use them in unexpected ways. As a side note, Edman states that their pen plotters are primarily sold to businesses, organisations and celebrities for handwriting-like applications (Edman, *13 Dec. 2021*; Edman, *13 Jan. 2022*).

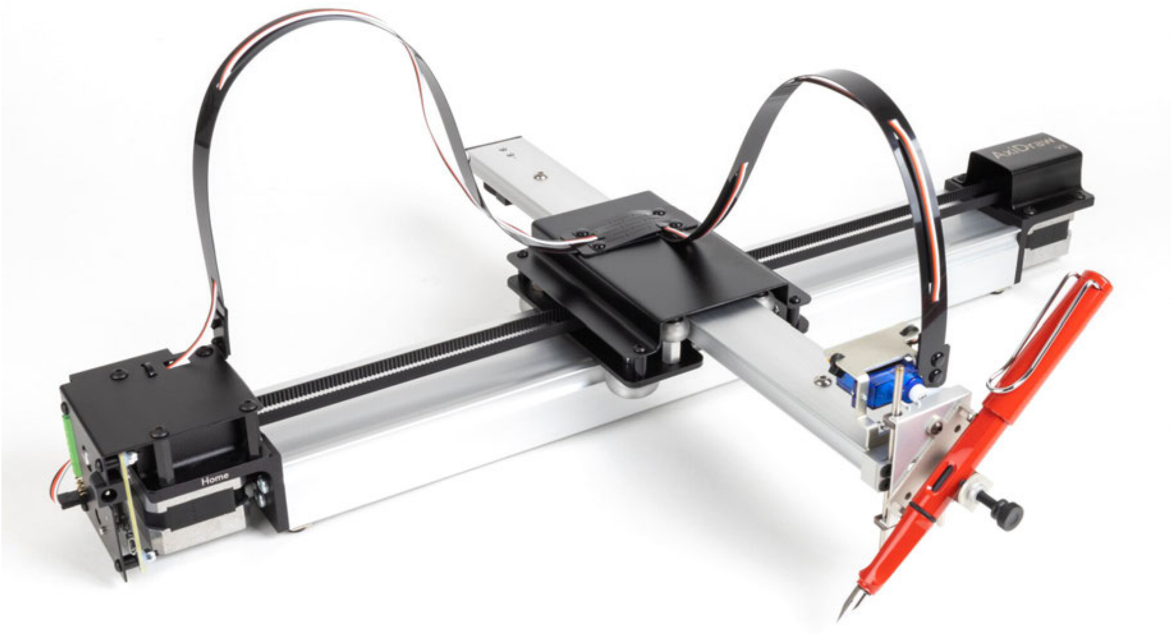


Fig. 11. AxiDraw, with a fountain pen.

The factors promoting the recent revival of pen plotters are connected to the growing interest in digital fabrication and the availability and affordability of hardware components and software to control plotters (Edman, *13 Dec. 2021*; Surguy). According to Maks Surguy, the fact that the output of pen plotters can serve as a source of income also contributes to their recent popularity. In Europe, there are still many vintage plotters, mainly from the 1980s, available on the market. While their prices fluctuate, they are still affordable and can be purchased for a small fraction of their original price (Jason, *12 Apr. 2022*). Edman said the plotter revival started in 2016 and plateaued after two to three years (Edman, *13 Jan. 2022*). Surguy believes that the popularity of pen plotters is still increasing. The Discord member Jason has observed oscillations in the plotter-related online communities' activity. He believes that during the pandemic, which forced many people to stay home, the interest in plotters increased (Jason, *12 Apr. 2022*).

2.5 Fascination

In 1985, the American PC Magazine published an extensive test of the most popular pen plotters of the time. Glenn Hart, the contributing editor of that article, notes: “I’ve had plotters on the brain (and ink on my fingers) for well over a month now. There is something magical and mysterious about them; watching a brightly coloured image take shape excites both computer expert and layman alike.” (Hart, *Adding a Touch of Color* 110) This testimony was exemplary for individuals operating pen plotters back in the day, as it is to date. Most, witnessing the pen plotter’s drawing process, are mesmerised. Maks Surguy explains that plotters are drawing robots extending our abilities, and the superhuman speed and precision with which they execute the commands puts the observers in awe (Surguy). Lenore Edman explains that almost no one can resist watching the movement of the pen on the paper. Furthermore, already in the time of mechanical automata, people were fascinated to watch mechanical movement. Referring to the noise of the stepper motors and servo, she adds that many of their customers are also fond of the acoustical component of the plotting process (Edman, *13 Jan. 2022*).

Artistic and experimental plots may take hours when consisting of thousands of lines. However, these extensive plots are the result of a process that is not without problems: The paper buckles while the moisture of the ink is increasingly seeping into its fibres, the pen might run out of ink, and its tip gets worn, possibly to a level where it cannot produce consistent lines anymore. A pen tip that is too hard and abrasive, on the other hand, pulls fibres from the drawing surface, which can clog the pen or tear holes into the paper. In short, planning and observing the plotting process is exciting. Therefore, a successful large plot depends on impeccable planning (Jason, *12 Apr. 2022*).

2.6 Community

The contemporary pen plotter enthusiast can rely on broad support from a growing online community. For example, the hashtag #plottertwitter is used for everything related to pen plotters on Twitter. In addition, novices and professional artists share their work, which is usually encouraged by positive and constructive feedback. Another peculiarity of the plotter community is the plotter postcard exchange #ptpx periodically organised by Paul Buttler, where members send each other plotted postcards.

Maks Surguy started 2018 with a Discord channel, drawingbots, which counts over 1400 members. On drawingbots, most questions are answered quickly and constructively. Moreover, the friendly tone and readiness to share knowledge are astonishing. Asked about their motivation to be so generous with their time and knowledge, Maks Surguy explains that sharing knowledge is always a two-way street where everybody can learn. This practice helps grow the community, resulting in more accumulation of ideas and knowledge (Surguy). Likewise, Jason on Discord, who is famously helping with anything related to vintage plotters, is happy to share his passion and to enable anyone interested to get old plotters back up and running again (Jason, *12 Apr. 2022*). According to Lenore Edman, the typical community members are from the field of engineering or computer science, which have the means to afford the necessary hardware. On the other hand, a few artists want to learn to code and use plotting hard and software as a tool (Edman, *13 Jan. 2022*). Maks Surguy notices that usual members are often programmers, developers, scientists, professors, and robotics engineers or students (Surguy).

3 PEN PLOTTERS AS AN ARTISTIC TOOL

Pen plotters were the first hard copy devices that could reproduce the graphical output of a computer program directly on paper. This immediate method of visualising graphics suggested new creative possibilities to scientists who had access to this revolutionary technology. At the same time, it was the desired solution for artists who have already worked with algorithms but had previously no automated way for visualisation. While numerically controlled drawing machines have an important place in early computer art history, they are still a valued tool in contemporary generative art. However, employing machines in the creative field has often been misunderstood, leading to questions about the authorship of a generative art piece.

While pen plotters can draw fast and exact without fatigue, their creative potential is limited when compared to drawing with pen and ink by hand. Especially the missing ability of pen plotters to dynamically change the way a pen is held or moved when drawing is reflected in the resulting uniform lines. However, utilising software solutions, which analyse a base image and generate the control code for the plotter, allows for more expressive drawings. Furthermore, there is much potential in building own devices or adapting existing pen plotters to gain abilities, which commercial plotters are lacking.

3.1 Pen plotters in early algorithmic art

Pen plotters had a crucial role in early algorithmic art, being the first hardcopy device to output graphics directly on paper. While impact printing devices such as line printers were already in use in the 1950s (Lee and Zable 131), they could only print characters. Another output device to reproduce graphics was the Stromberg-Carlson 4020, a computer-controlled microfilm plotter utilising a cathode-ray tube. The SC420 allowed plotting onto film, which had to be developed before the film could be used to enlarge the graphic onto photo paper. A. Michael Noll employed this technology at the Bell Lab in New Jersey, and his resulting work was shown at Howard Wise Gallery in New York in April 1965 (Patterson 26). However, the pen plotters utilised by two other pioneers of algorithmic art, Georg Nees and Frieder Nake, allowed them to plot directly onto the paper. Both had access to a Zuse Graphomat Z64, an exact drawing machine that could plot in colours, depending on the pen mounted to its mechanism. As a result, Nees, who worked at Siemens, could showcase his first works at the public premises of the Technische Hochschule Stuttgart in February 1965, which is known as the first exhibition in the new genre of computer art. After seeing Nees' work, Nake, who worked there as an assistant, was driven to have his own exhibition. Thus, in November of the same year, Nees and Nake had their work shown at the Galerie Wendelin Niedlich in Stuttgart (Nake).

The engineer Noll and the mathematicians Nees and Nake had all technical backgrounds, which allowed them access to the expensive computer equipment of the early 1960s. For example, Nake says that he was tasked to write an interface to connect the newly acquired Zuse plotter with the institute's existing computer in 1963, which led him to write algorithms producing graphics to test his work (Nake). Exemplary for all three digital pioneers is that their artistic work was promoted by their knowledge and access to new and revolutionary computer systems.

Nevertheless, a few artists with a non-technical background also embraced the possibilities of early pen plotters. The painters Manfred Mohr and Vera Molnár started using pen plotters at the end of the 1960s. There are parallels in their pre-digital works: Molnár made paintings based on rules, which she defined beforehand; she called these algorithms “machine imaginaire”. After learning to program in Fortran, she was permitted to use a computer and plotter at a research facility (The Mayor Gallery). Similarly, Mohr got access to a computer in 1969, allowing him to study the use of Fortran. Initially, Mohr did not have access to a pen plotter and was forced to transfer the calculated coordinates by hand onto paper (Rosen 141). Later the same year, he heard that the Météorologie Nationale in Paris had a plotter. Mohr explains that he immediately knew that this would solve his problem. As a result of his persistence, he was eventually allowed to use the computer and plotter of the Météorologie Nationale, where he could work on his computer graphics for 11 years (Mohr).

While the access to early pen plotters encouraged scientists to engage in artistic activities, plotters finally allowed artists to produce the resulting graphics of their well-planned algorithms directly on paper.

3.2 Pen plotters in current art and design

Today, computers are ubiquitous, powerful, and affordable, while information can easily be obtained online. Most persons interested in generating computer graphics based on algorithms or writing programs that alter existing digital images can get the necessary software tools for free. Comprehensive books such as “Generative Design” (Bohnacker) serve as an in-depth guide. Furthermore, various forums and platforms run by a dedicated community whose members are usually happy to provide support lower the frustration when help is needed. Consequently, the threshold to start with generative art and design has never been as low before.

Data visualisation is another field of contemporary generative design. As a consequence of data collected by organisations such as Statistics Finland, mainly being public, anyone can access their database online (Statistics Finland) to be visually processed. Also, with its increasing number of devices, the Internet of things can serve as a source of data. In addition, free software environments such as R (The R Foundation) allow vast data to be processed and visualised. Raw or processed data can serve as a base for generative designs. Furthermore, external data can be used instead of random numbers as parameters of an algorithm influencing the visual outcome.

Modern pen plotters developed for creatives are quickly assembled and ready to run. More affordable surplus vintage plotters are available on the market; they usually still work well after more than 40 years and can be connected to modern computers with little effort. It is similarly inexpensive to build a plotter with components from multiple sources, accommodating the maker and DIY scene. These projects require more knowledge about mechanics, electronics, and programming, but open-source plans and software are available.

Using pen plotters is a logical consequence for many generative designers and artists: While it has been possible to print graphics in museum quality using inkjet printers for a long time, the process of using a pen plotter is much more interesting: There are many factors contributing to the outcome, such as plotting speed, pen pressure, the drawing medium, and the drawing implements. Therefore, pen, ink and paper are usually chosen with much prudence. Also, the difference that pen plotters are based on vector graphics while modern printers are based on raster graphics is an essential contributor to the popularity of the former, mainly to output line based graphics: A line drawn on paper by a pen looks more appealing than an interpolated, pixel-based imitation. While primarily commercial vintage plotters can draw very precisely and accurately on smooth paper, it is possible to achieve an adverse effect, for example, by plotting on paper with an irregular surface. The contrast between the exactness of the digital data and the, at least to some extent, unpredictable outcome of the plot can be compelling and is often desired.

A drawing implement can be attached to virtually any numerically controlled device moving on two axes, such as FFF 3D printers, laser engravers or cutters, typewriters, robotic vacuum cleaners etc., offering countless possibilities. Also, the medium applied onto the drawing surface and the means of applying it are diverse. Consequently, the borders between pen plotting and additive manufacturing methods are being blurred: Using extruders allows, for example, to draw with icing on a cake, deposit bacteria to grow them in defined patterns (Surguy), or dispense other materials. The artist Ted Lawson plotted a life-size nude self-portrait using blood straight from his body (Plante). Nevertheless, most artists and designers are using their pen plotters in conventional ways, by using a drawing implement to plot on paper.

3.3 Pen plotters in art and the question of authorship

While the discussion about authorship is present throughout art history, it gained a new dimension with the introduction of computers in art. Whether works made by computers can still be called art has been thematised in numerous papers, especially connected to *Cybernetic Serendipity: The Computer and the Arts*, which was one of the earliest and undoubtedly the most extensive exhibition featuring early computer art. This exhibition, shown in 1968 at the Institute of Contemporary Art in London, was poorly received by the art world. Especially the combination of creativity and modern technology was confusing the critiques (Fernandéz; Ussleman).

The claim that the computer makes the art is the result of misunderstandings about the process of computer-based art: The working methods used when creating generative visual work in an artistic context show much more involvement than a superficial glance would suggest. Manfred Mohr, for instance, compares the process of algorithmic art with the three states of matter: Firstly, an algorithm has to be written. Secondly, the algorithm has to be run to generate an output. Finally, the output has to be plotted. He says all three states are part of the artwork (Mohr). Comparatively, Frieder Nake describes his process as follows: “Ich denke also ein Konzept; ich formuliere es als Programm; der Computer rechnet danach; ein Gerät zeichnet oder projiziert das Ergebnis; ich wähle aus, was ich behalte” ‘So I'm thinking a concept; I formulate it as a program; the computer then calculates; a device draws or projects the result; I choose what I keep’ (Weisser). The author of an algorithm, which results in a perceivable work, is ultimately at least co-author of the work. Consequently, one could argue that declining the creator of an algorithmic artwork, the authorship in favour of the executing computer and output device can be compared to denying a composer to be the author of a musical piece in favour of the performing orchestra. Importantly, this analogy is valid given that the composer does not also claim to be the orchestra, its instruments and their inventor. Hence, it has to be noted that all computer-based art builds on the work of skilled individuals responsible for developing all the utilised hard- and software. Consequently, the algorithmic art pioneer Frieder Nake signed many of his earlier works with "NAKE/ER56/Z64" (Digital Art Museum), also giving credit to the computer system Standard Elektrik Lorenz ER 56, which was calculating his algorithm and the Zuse Graphomat Z64, which was drawing its output.

Access to the algorithm written by other authors makes it possible to regenerate similar output, at least on screen, without much knowledge or skill. Consequently, plagiarism is common in the field of generative art. Namely, in the plotter community, original authors often share their methods or complete programs with others. Unfortunately, incidents of dishonest appropriation have diminished the willingness to continue with this generous practice (Jason, *12 Apr. 2022*).

3.4 The shortcomings of pen plotters as a creative tool

Commercial pen plotters are designed to hold a pen vertically. The pen-lift mechanism can lift the drawing implement up to a predefined height over the drawing surface and lower it down onto the drawing surface. It is held down either by its weight, a spring, or electromagnetism. In Addition, some pen plotters allow the adjustment of the pen pressure and can automatically change between different pens, filled with differently coloured ink and feature different sized tips. In brief, most commercial pen plotters were designed to reproduce technical or architectural drawings or draw professional-looking business graphics. Consequently, their mechanical design and control language reflected their common purpose: To draw precise and accurate vectors in constant line widths.

Many techniques which feel natural when drawing or painting by hand are impossible to achieve with a pen plotter. They don't allow changing the holding angle dynamically, the height, or the pressure with which the drawing implement is used. Also, all drawing implements used in pen plotters are ink-based. Their viscosity has to allow the ink to flow freely but consistently out of the used felt tip, roller-ball or technical pen.

It would be unreasonable to compare the pen plotter to manual drawing or painting techniques other than the ones employing pen, ink, and paper. However, this artistic medium allows “an enormous variety of individual expression, whose possibilities can never be exhausted” (Smith et al. 112) while comprising nipped pens, markers, technical drafting pens, ballpoint pens, and brushes. Artists drawing with ink are often moving their whole forearm while modulating the resulting lines with the movement of the hand from the wrist. In comparison, pen plotters are inherently limited in changing how the pen is held and moved dynamically (see table 1).

Table 1:

Comparison of drawing with advanced commercial pen plotters to drawing by hand:

	Drawing with a pen plotter	Drawing by hand
Accuracy, precision and repeatability	Very high	Low, (depending on skill)
Dynamic change of direction	Yes, immediate and at an accurate angle	Yes, with the possibility of smooth transitions
Dynamic modulation of pen's angle (tilt)	Static, in vertical position or at a fixed angle	Yes
Rotation of pen in pen's axis	No	Yes
Dynamic modulation of pen pressure	Can be changed between line segments	Yes
Dynamic modulation of pen hight	No	Yes
Dynamic modulation of speed	Can be changed between line segments	Yes
Dynamic change of acceleration	No	Yes

3.5 Software techniques to circumvent the pen plotters' disadvantages

While a pen plotter's expressive abilities are limited compared to those of the human hand. Pen plotters have two significant advantages: They draw exact, fast and without fatigue. Consequently, these advantages can be used to compensate for the reduced expressiveness. Pen plotters can draw tens of thousands of line segments or exact circles as long as they are supplied with the necessary control data and power and as long as the pen is in working order and has sufficient ink. The control data can be generated by an algorithm that analyses an image's brightness values, which serves as the base of an artwork. The algorithm subsequently calculates the density of the ink in a particular area, and the control data is generated according to the set strategy and parameters defined by an artist.

Such strategies are based on the principle of varying the density of the drawn lines or points, influencing the darkness of an area. The combination and arrangement of those line segments are where those strategies differ and allow for creative experimentation. One approach is drawing parallel lines (see fig. 12), concentric circles or spirals while introducing waves with the line's path as its centre. The resulting squiggly lines can be altered in frequency to affect how close they are together and in amplitude, determining how far the waves move from the centerline.

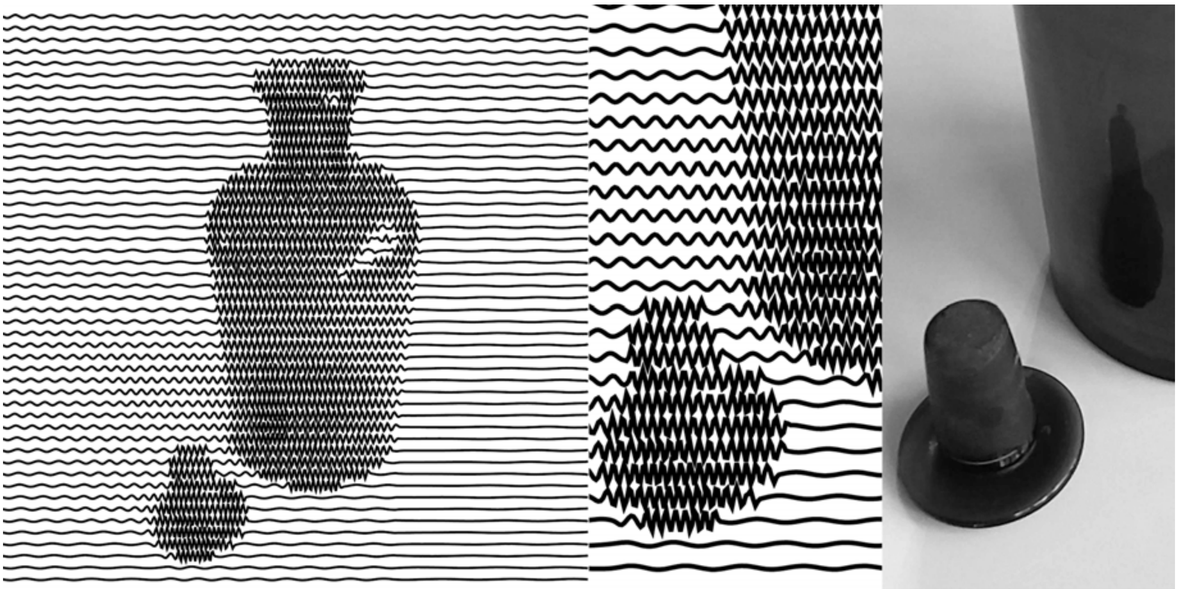


Fig. 12. Halftone image realised with squiggly parallel lines, detail thereof, and detail of the original photograph.

The second commonly used strategy is to repeatedly plot similar or random shapes in varying density and size. The shapes can be overlapping or be packed next to each other (see fig. 13). Consequently, there is additional creative potential when combining these methods, such as using letters as symbols, which result in texts aligning along a path, to name one.

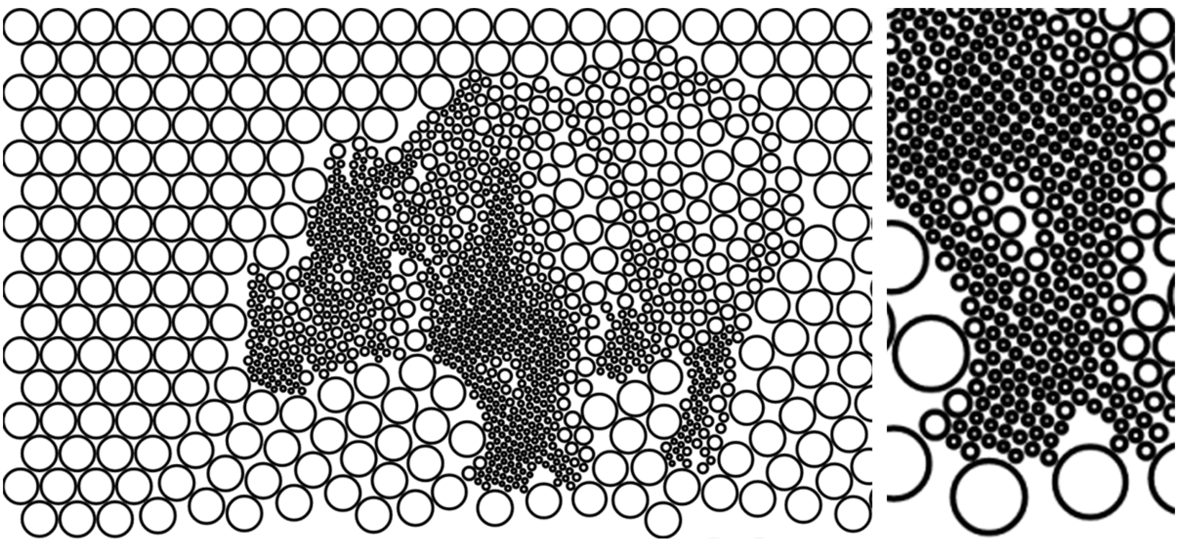


Fig. 13. Halftone image realised with circles of different sizes and detail thereof.

There are parallels between some of the techniques possible when using pen plotters and the ones employed by artists drawing by hand. Stippling and pointillism are two, where countless short line segments or points are applied on paper. Above all, even colour images can be reproduced when colour separation algorithms are applied, and the result is plotted using pens of different colours.

Many plotter-specific software solutions to generate halftone images are made available online by their authors. Some of them have polished user interfaces, which invite experimentation.

3.6 Possible improvements to enhance the abilities of a pen plotter

Deviating from traditional pen plotter designs allows for making several improvements concerning the diversity of its abilities. Contemporary commercial pen plotters allow fastening any pen or brush into the penholder and are not restricted to using proprietary pens from only a few manufacturers. In addition, some pen plotters allow for the angle of the pen to be set, which allows for using special writing and drawing implements such as nipped pens.

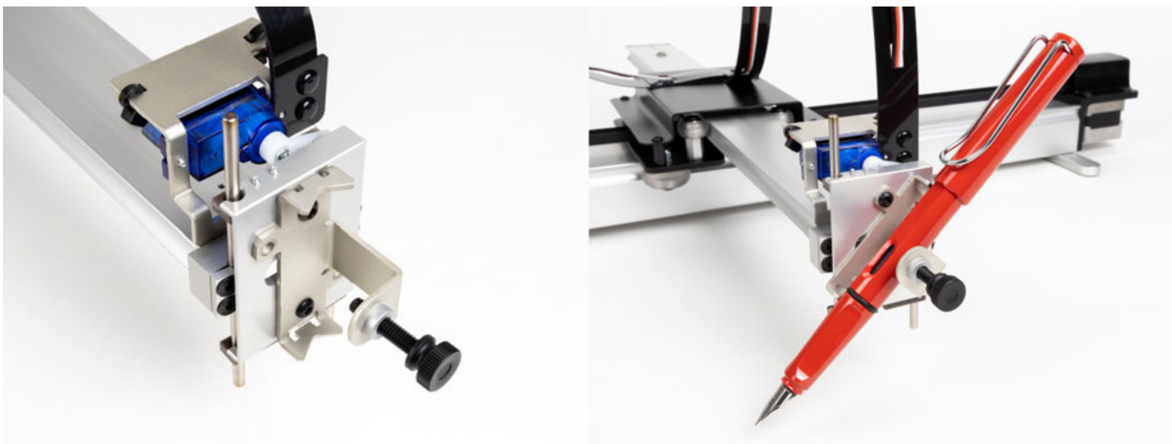


Fig. 14. Pen-lift mechanism of an AxiDraw plotter with pen holder in the vertical position and set to 45°.

Another possibility is improving the pen-lift mechanism allowing the pen's angle to change dynamically using an additional servo or motor. It might also be possible to design a pen holder which can rotate a pen or brush on the vertical axis. A combination of these two methods could be utilised for calligraphy effects when using pens with chisel nibs.

Finally, building a pen-lift mechanism that allows the pen height to be dynamically controlled with the necessary precision and accuracy promises to yield intriguing results by dynamically controlling the weight of lines using brushes or fibre tip pens with conically shaped tips. While this solves a specific problem, the advantage of this solution is that the mechanical design is comparingly less complex, promising a greater probability of resulting in a usable solution allowing for experimentation.

3.7 Criteria to verify the pen plotter's enhancements

The results of the experimentation with the new pen-lift mechanism should reflect the ability to draw lines with dynamically changing width. The developed software should be able to generate control code to emphasise the abilities of the new design. In addition, the results of this research will be compared to similar works done by other members of the plotter community.

4 DOCUMENTATION OF THE EXPERIMENTAL PEN PLOTTER

Obtaining a machine that allows for experimenting with different pens and brushes was a priority for this work. Adapting an existing commercial pen plotter would have been difficult due to their construction, leaving little room for additions, physically and in the machine's closed-source firmware. Similarly, building a pen plotter from scratch did not seem a practical solution either, considering that the focus of this work should lie in the experimentation and exploration of new possibilities offered by modifications made to a pen plotter. As a result, converting an open-source laser engraving machine to a pen plotter was the most viable option.

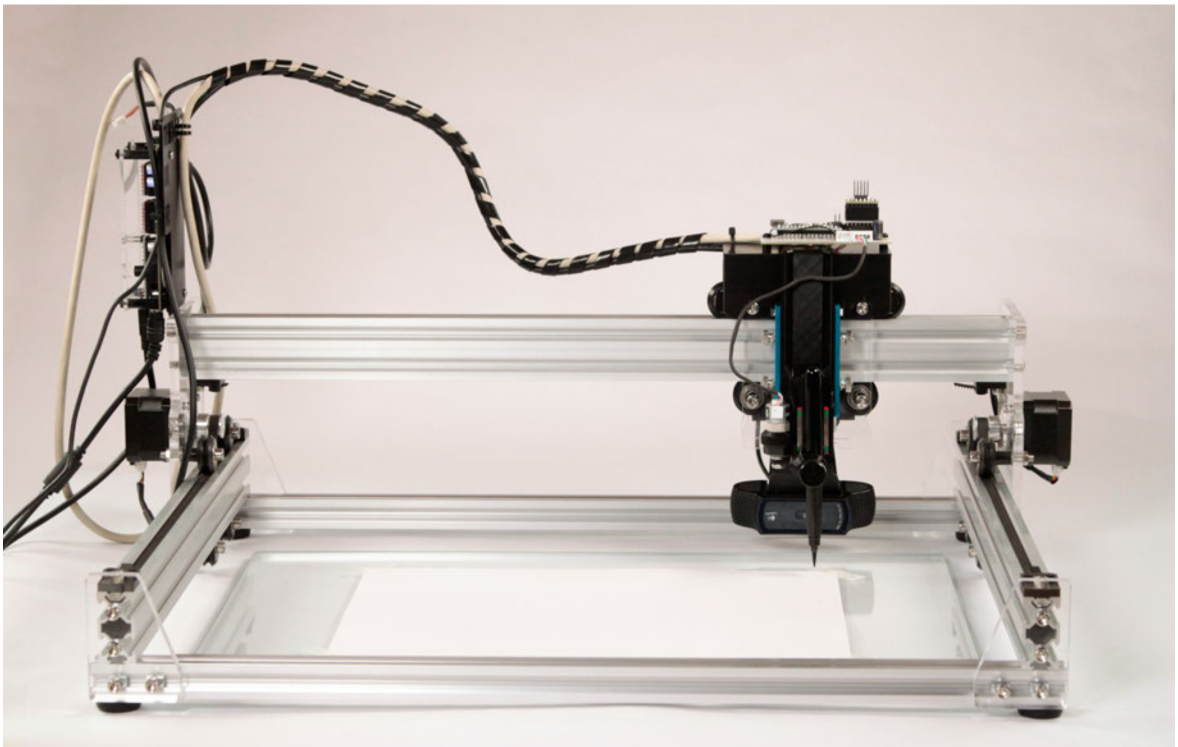


Fig. 15. The resulting experimental pen plotter.

4.1 Conversion of an open-source laser engraving machine into a pen plotter

The decision to convert an existing laser engraver to a pen plotter was mainly based on its similar design. Both the laser engraving machine and the pen plotter require fast movement of the laser or pen on the horizontal plane. In addition, both devices need to be controlled with high accuracy, precision, and repeatability to produce results of satisfactory quality. The same also applies to 3D printers operating with fused filament fabrication, or FFF in short. However, FFF printers have a slow Z-axis and feature additional functionality to control the heated printing bed, the extruder's heating and several cooling fans. Therefore, while it would be possible to convert an FFF printer to a pen plotter, 3D printers are not ideal as a base for such a conversion. Furthermore, compared to 3D printers and especially CNC milling machines, the forces in pen plotters and laser engraving machines are comparably small and primarily the result of the acceleration and deceleration in the horizontal plane. Therefore, the later machines are designed to keep the weight of the moving parts to a minimum while remaining rigid.

The key differences between a laser engraving machine and a pen plotter lie in their tools. Laser engraving machines feature a laser burning the surface of the workpiece to mark it. Therefore, the laser's output needs to be turned on and off. Some more advanced engravers allow controlling the output power of the laser to vary the intensity of the laser beam. On the other hand, a traditional pen plotter needs to lower the pen onto paper to transfer the ink onto the drawing surface. Usually, pen plotters accept the two commands, pen up and pen down, to control the pen's position in relation to the paper. Some advanced pen plotters also accept additional commands to define the pressure with which the pen is pressed onto the drawing surface. As a result, the laser module has to be replaced by a mechanism allowing it to lift and lower a pen to convert a laser engraving machine into a pen plotter. Controlling a pen-lift mechanism instead of a laser requires changes to the control electronics.

In terms of operational safety, it is generally a bad idea to operate these cheaper laser engravers, as they are designed without a housing protecting the eyes from the blinding effects of the laser beam, which is still dangerous even when reflecting off a surface. Many kits are supplied with protective eyewear; however, the effectiveness of these should be questioned. While they protect, in the best case, the eyes of its wearer, they offer no protection to bystanders and pets. In addition, the smoke resulting from burning the workpiece can be harmful to health when the device is operated in insufficiently ventilated spaces. Pen plotters, on the other hand, are comparably safe to use.

The previous considerations led to the decision to purchase an EleksMaker EleksLaser-A3 Pro. However, buying this DIY kit instead of buying the individual parts also had economic benefits: The sum of the cost of all necessary parts purchased separately would likely have been higher than the cost of the complete kit, which was less than 200€ delivered. In addition, the construction and quality of the EleksLaser-A3 were already tried and have proven to be working reliably.

The chosen laser engraving machine is primarily constructed of 2040 T-slot Aluminium Extrusions and laser cut acrylic parts. Thus, the device has a sturdy frame designed in a gantry configuration, which means that its horizontal member is supported on both sides. The gantry is driven by two stepper motors, which allow quick accelerating and deceleration of a higher mass. Also, the mounting bracket of the laser module promised to make the conversion easier.

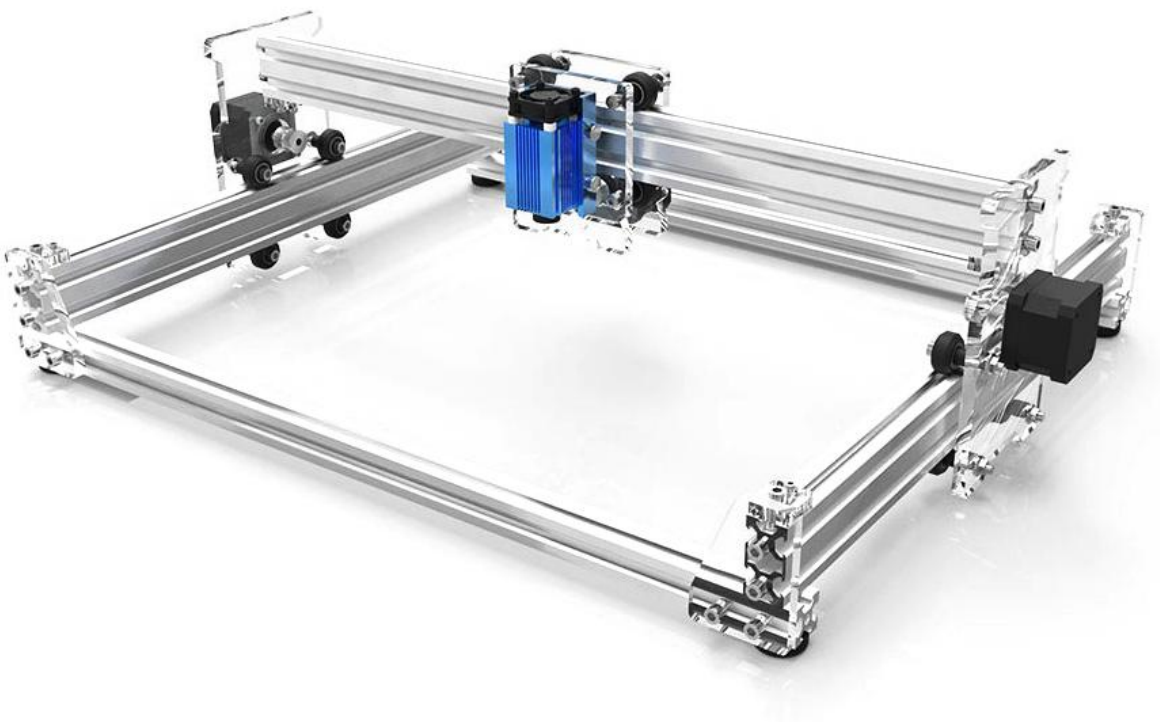


Fig. 16. Laser engraving machine EleksMaker EleksLaser-A3 Pro

The final dimensions of the converted pen plotter, including all the additions and modifications, require a free table area of 600 mm x 450 mm to operate, and its overall height is 330 mm. The usable area on which can be drawn is 376 mm x 268 mm, slightly smaller than the DIN A3 format.

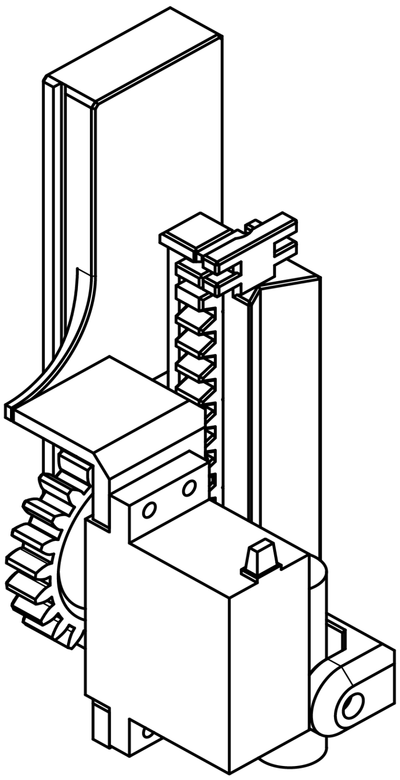
4.2 The pen-lift mechanism

The primary function of a pen-lift mechanism is to keep a plotter’s pen above the paper unless ink needs to be transferred onto paper. Therefore, the pen or other drawing utensil needs to be held in the upper position while the plotter is idle or moving to a new drawing position, i.e. during rapids. Furthermore, the drawing utensil has to be held firmly perpendicular to the drawing surface while it is in contact with the medium during the drawing process. The pen-lift mechanism consists of an electromagnetic solenoid or voice coil acting against a spring in commercial office pen plotters. In pen plotters which are still in production and targeted at artists, the mechanism consists of a hobby servo, which holds the drawing utensil in the up position and allows it to be lowered onto the paper, where it is pressed onto the drawing surface by its weight instead. Both mechanisms are usually configured to move to the predefined up and down positions. Thus there is no possibility of influencing the stroke weight by controlling the drawing utensil in relation to the drawing surface.

For the conversion of the laser engraving machine to a pen plotter, a pen-lift mechanism had to be designed, its parts produced and assembled, and a suitable way to control the mechanism had to be developed. Considering that this thesis's practical work's main objective is to experiment with a pen-lift mechanism allowing precise control of a pen or brush tip in relation to the drawing surface, sufficient steps between the highest and lowest positions were necessary for accurate and precise vertical positioning. Other noteworthy characteristics of the pen-lift mechanism are its speed and maximal stroke. The time it takes to complete a plot is strongly influenced by the possible maximal rate of the pen moving up and down: The pen carriage must often remain stationary during the pen's vertical movements before or after drawing a line. Moreover, when using drawing utensils with viscous ink or paint, the ink or paint starts to be transferred to the paper as soon as and as long as the drawing utensils are in contact with the surface, resulting in undesirable dot gain at the start and end of a line. The stroke of the pen-lift mechanism is the maximal achievable distance between the upper and lower position. A higher stroke adds further possibilities, such as lifting a brush over the edge of a water container to rinse it or picking up water when working with watercolours. Generally, a higher stroke comes at the cost of lower speed, resolution, precision and accuracy.

Two versions of the pen-lift mechanism were designed and made to gain the possibility to utilise both a long stroke and high precision. The process of making the mechanisms was similar. They were designed in Autodesk Fusion 360 - a 3D computer-aided design and manufacturing software, which allowed the export of the surface geometry of the individual components as STL files, which are commonly used in 3D printing. These files were opened in PrusaSlicer to prepare and convert the data to be printed with an FFF 3D printer. All parts were printed on a Creality CR-10 with the biodegradable thermoplastic polylactide, commonly known as PLA. This rapid prototyping approach allowed for quick iterations: Several design revisions were needed until everything fit and worked as intended. Both pen-lift mechanisms are based on linear guideways, which ensure a high rigidity while having very low friction in their movement. In both mechanisms, pens of various diameters up to 15 mm can be fastened securely by tightening a knurled bolt.

The pen-lift mechanisms can be attached in the same bracket initially designed for the laser module to be secured. The pen-lift mechanism can be secured with four bolts, which are tightened by hand. In addition, the attachment allows the whole mechanism to be adjusted in height to accommodate different writing and drawing implement designs.



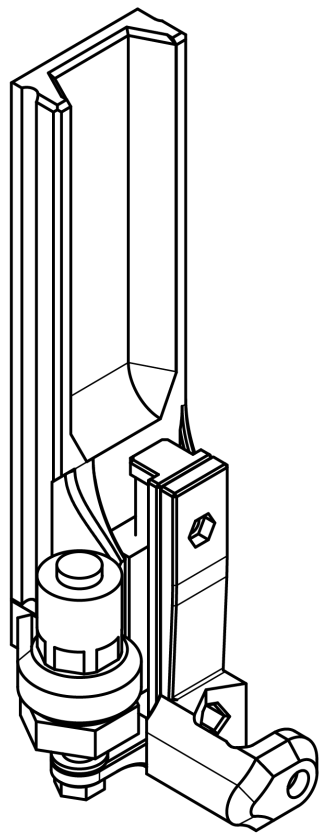


Fig. 17. Pen-lift mechanism versions 1 and 2

Pen-lift mechanism version 1 with a long stroke

The first version of the pen-lift mechanism was designed with a rack and pinion, which translated the rotational movement of an RC servo, commonly used in radio-controlled cars and other toys, into the linear motion to lift the pen. The main difference between the rack and pinion design and other designs utilising servos is that in the latter, the movable part of the mechanism is lifted by the servo's horn, attached to the servo's shaft. As a result, the pen's motion rate is not linear compared to the angular motion at the servo's shaft, leading to problems when it is desired to control the exact distance between the pen's tip and the drawing surface. Another benefit of my design is that the motion is mechanically coupled and can be controlled in both ways. Hence there is no dependence on gravity or springs.

The play inside of the servo's gears added to the tolerances of the rack and pinion, which are typical for 3D printed parts, led to some backlash in the mechanism. Additionally, it was necessary to design the platform holding the pens in a way that it is suspended by short rubber bands, which prevents damage to the pen, the mechanism or other parts of the plotter when using a pen or pencil with a sturdy tip and when colliding with the drawing surface. Unfortunately, this decreases the achievable precision and accuracy of the mechanism even more. For future designs, it will be interesting to experiment with compliant mechanisms acting as a suspension in the direction of the lifting motion. Such mechanisms would compensate for some inaccuracy and irregularity of the drawing surface while remaining very firm in the other two axes. Moreover, a redesign of the mechanism might allow for some weight savings. The weight of the current design is 182 g, which is in favour of higher possible plot speeds.

The initial plan was to control the servo directly from the EleksMana SE v3.2 control board included in the laser engraving machine kit. This function was documented, and the board offers header pins to plug in a servo's leads. This feature was intended for lifting mechanisms, setting the pen on the paper and relying on gravity or springs, as described above. However, due to the limitations of the microprocessor, the resulting resolution of the new mechanism would only be 1,9 mm, and not sufficient for the desired experiments. Fortunately, it was possible to circumvent these limitations by adding a second processor. This addition allowed the pen-lift mechanism to be controlled with a resolution of 0,033 mm. This number is more than adequate, considering the mechanical limitations of the whole system.

The main advantage of this mechanism is, however, its long stroke of 65 mm allows for a pen or brush to be lifted high enough to clear obstacles like the wall of a water container or ink well. Experiments showed that the speed with which the pen can be lifted and lowered is 64 mm/s, relatively low but arguably sufficient when working with liquid inks or watercolours.

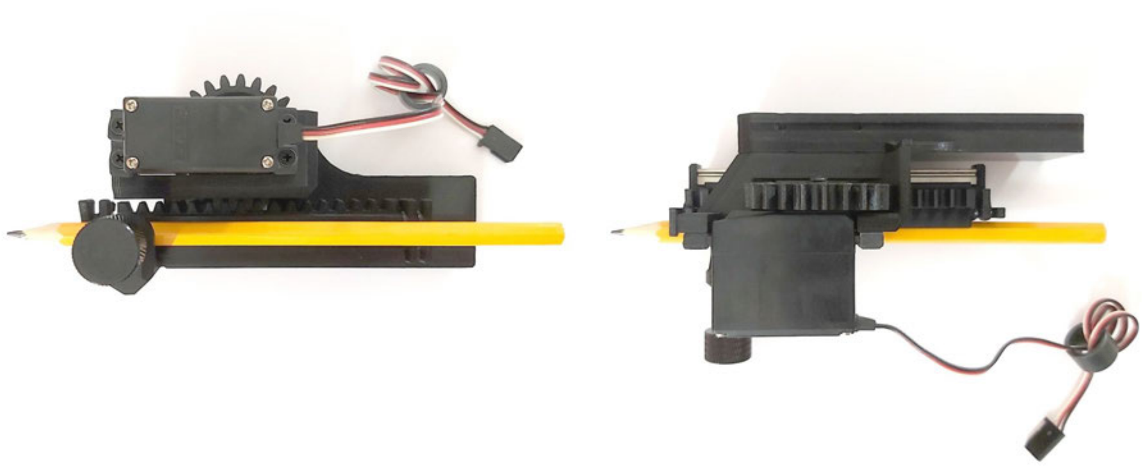


Fig. 18. 3D printed pen-lift mechanism versions 1 with a pencil for scale

Pen-lift mechanism version 2 with high precision, and accuracy

Experiments with the first version of the pen-lift mechanism showed that its play and backlash did not allow control of the height and the resulting compression of an inkbrush's tip precisely enough to affect the resulting stroke width satisfactorily. Also, the suspended floating platform holding the pens allowed the pen to move on the vertical z-axis and the horizontal y-axis, which led to an unpredictable outcome of the drawing. The quest for more precision and accuracy led to considerations to build a second version of the pen lift mechanism.

The first version has a long stroke, allowing experimentation with less precise drawing utensils. Therefore, it made sense to lay the main objective of the new version on a very sturdy design with minimal mechanical play. Also, in the new version, the vertical movement was guided along a precision ground linear guideway with no notable play on the other axis. The shorter required stroke allowed, in addition, to use a shorter guideway which reduced the overall weight of the mechanism, also in combination with other design improvements, to 109 g.

A linear actuator with a captive lead screw drives the lift mechanism of the newly designed mechanism. These actuators are targeted for high precision applications and are priced accordingly. However, they can be found as surplus at a fraction of their original cost. The actuator has a diameter of 15 mm and weighs only 15 g, coupled with a resolution of 0,02 mm or 0,0025 mm with micro-stepping. Therefore, it is ideal for the purpose. Furthermore, later experiments have shown that the achievable speed is sufficient. As a result, it is possible to lift the pen 3 mm in less than ⅓ of a second, including acceleration and deceleration.

An additional design improvement, as a result of findings from the practical application of the first version, is that the pen holder is open from the opposite side of the motor, which makes it easier to insert a pen. This improvement is especially noticeable when working with brushes or brush pens: It helps to avoid the transfer of ink or paint to the mechanism while mounting it.

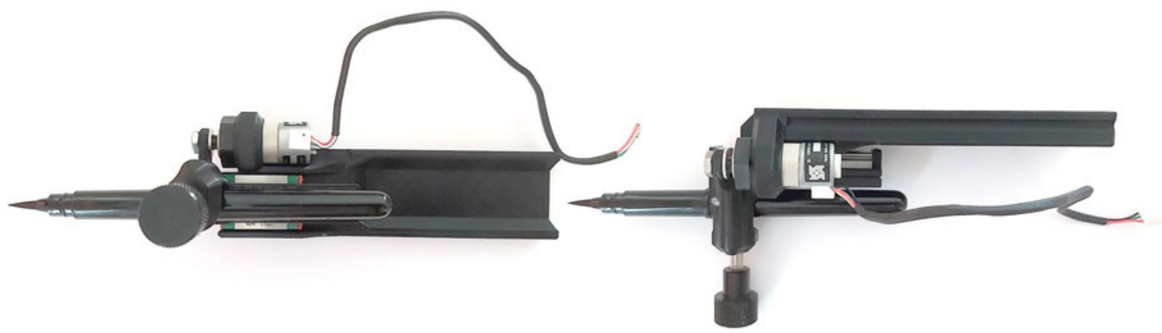


Fig. 19. 3D printed pen-lift mechanism versions 2 with a brush pen for scale.

Table 2:

Technical data of the two pen-lift mechanisms:

	Version 1	Version 2
Stroke	65 mm	12 mm
Weight	182 g	109 g
Max. linear force	48 N	35 N
Max. pen diameter	15 mm	15 mm
Resolution (with micro-stepping)	0,033 mm	0,02 mm (0,0025 mm)
Effective speed incl. acceleration and deceleration	64 mm in ca. 2 s	10 mm in 309,2 ms
Time needed for 3mm pen-up/pen-down	Ca. 300 ms	140,4 ms
Linear guideway	LML9B 95 mm	LML9B 55 mm
Actuator	Servo	Linear Actuator
Actuator manufacturer	Futaba	Haydon
Actuator type	S3001	LC1574W-04-025
Actuator weight	45,1 g	15 g
Actuator wiring	3 wires: GND, VCC, Signal	Bipolar 4 wires

4.3 Other additions and modifications to the pen plotter

In the original design of the EleksMaker EleksLaser-A3 Pro, the cable management and the controller's position, which should have been located at the back of the frame, were far from ideal. First tests showed that the cables leading to the gantry were dragging on the drawing surface in the initial configuration, which is not practical when working with ink or paint. Furthermore, there was no possibility of relieving the moving cables from strain and subsequently from stress on its connections, leading to premature failure. The gantry based design of the machine and its two motors which can drive a considerable mass led to the decision to mount the control board on the side of the gantry. Therefore an additional platform to mount the controller board and secure all cables were designed and manufactured using the 3D printer.

The counterpart, a platform mounted on the pen carriage, was also drawn up in the CAD application and printed in PLA. The second platform allows mounting an additional circuit board to control the two different pen lift mechanisms. Also, on this platform, cables can be secured using cable ties acting as strain relieves.

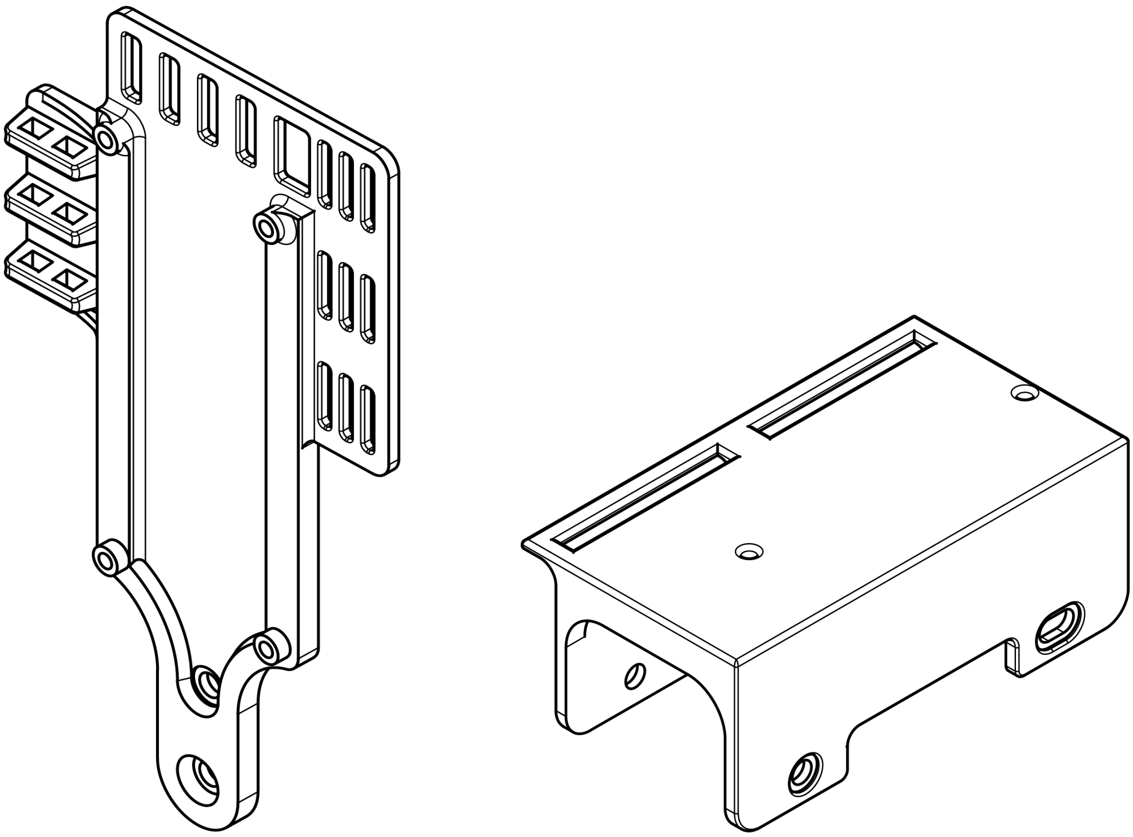


Fig. 20. Platforms that can be mounted to the gantry and the pen carriage holding the controller boards and securing the cables.

For documentation purposes and considering the joy of sharing the accomplishments with other like-minded individuals, it was essential to be able to record videos of the plotting process. Numerous experiments with different camera setups, ranging from a USB microscope to a DSLR camera attached to the various parts of the plotter, with occasionally adventurous methods, were conducted. However, the prospect of capturing the operation from a first-person view, where the camera is attached to the pen carriage and the pen is in focus and in the centre of the frame, seemed the most interesting. The Logitech B910 HD camera was ideal for the purpose: It features an included tilting mechanism making vertical adjustments easy. Also, its full HD resolution and the focus, adjustable with the accompanying application, stand out.

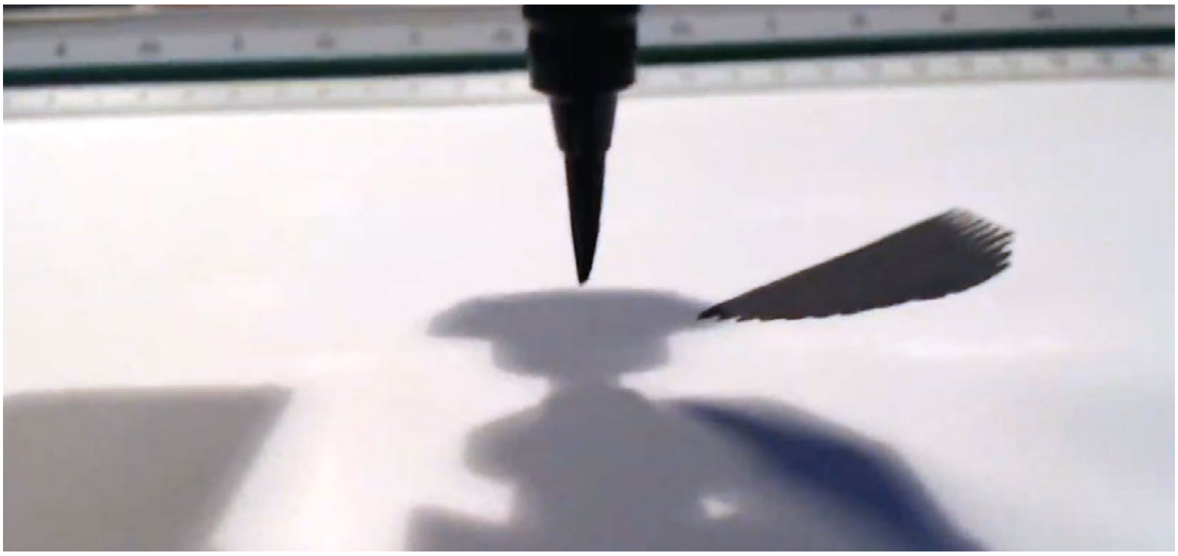


Fig. 21. Video still taken with a webcam mounted to the pen carriage.

The housing of the stepper motor driving the pen carriage was chosen as the best option to mount the camera firmly. Hence, a mounting bracket for the camera was designed and manufactured.

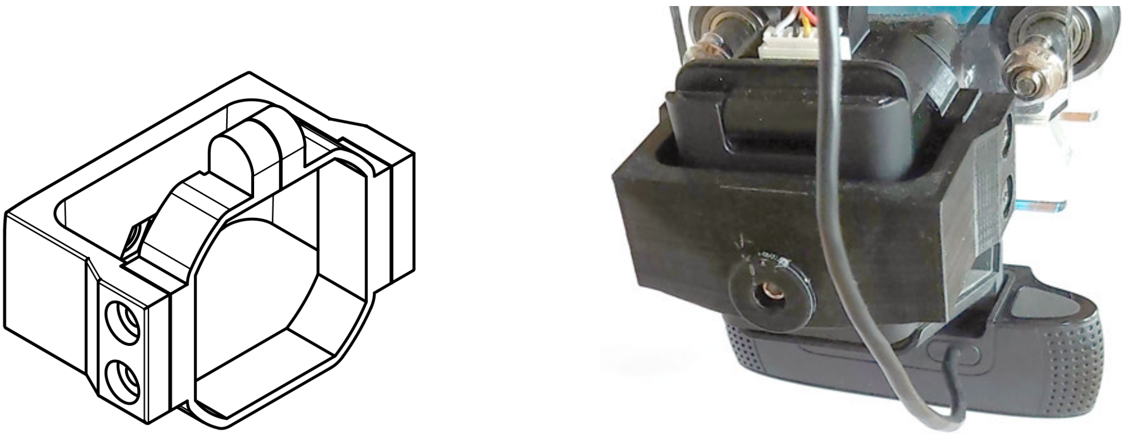


Fig. 22. Mounting bracket for attaching a webcam to the pen carriage

The footage recorded from the first-person perspective can, for example, be combined with an overhead shot recorded from a smartphone on a tripod resulting in a visually engaging video. For artists, having appealing videos is an essential factor in getting exposure on social media.

4.4 Controller

The driver board EleksMana SE v3.2, included in the laser cutting machine kit, is based on the popular and extensively documented Arduino Nano hardware board. The board has outputs for the two stepper motors driving the gantry and one to connect the motor driving the pen carrier. In addition, the board features outputs intended to drive the laser module and an output for a servo. The board is powered by a 12 VDC power supply which is also sufficient to power all motors.

The board contained EleksMaker proprietary firmware, which they call EleksROM. It works together with their windows software for creating laser engravings, aptly named EleksCAM. In addition, the Arduino Nano board allows being flashed with the Arduino bootloader and then programmed with the Arduino IDE, a necessity to gain the ability to load Grbl onto the microcontroller.

Grbl is open-source software for motion control of machines written for the Arduino platform (Jeon). A motion control software accepts instructions in a specified programming language and interprets and converts these into signals controlling the actuators to execute the motions. The motion control software takes real-world physics into account, which manifests itself in smooth movements of the tools or, in this case, the plotter's pen carriage. The controller plans the movements ahead of their execution, resulting in the correct acceleration and deceleration rates for all motors. The Grbl controller requires the instructions sent via the USB in the computer numerical control programming language G-code.

Initial attempts to control the servo using the servo output of the EleksMana board did not lead to any satisfactory results. The servo is controlled by a signal consisting of regular short pulses, which are modulated in their length depending on the desired angular position of the servo’s shaft. The length of the pulses is between tens and a few thousands of microseconds. To generate these signals is a demanding task for a microcontroller, especially considering that, at the same time, other functions for the motion control have to be performed. While a version of Grbl motion control software is available to drive servos, the resolution is, due to the constraints of the microcontroller on the Arduino Nano board, limited to about 2 mm in the case of the first version of the pen-lift mechanism. This resolution is sufficient when using conventional mechanisms with servos but far from the requirements for this project, which led to the decision to use a secondary microcontroller to generate the pulse with a modulation signal. A prototype (see fig. 24) utilising an Adafruit Trinket Mini Microcontroller showed that this is the right approach. Later the Trinket was exchanged for an additional Arduino Nano board, mounted on the pen carriage, performing additional tasks to control the second version of the pen-lift mechanism. Furthermore, both pen-lift mechanisms can be plugged into the secondary controller board, making changing between them quickly and easy.

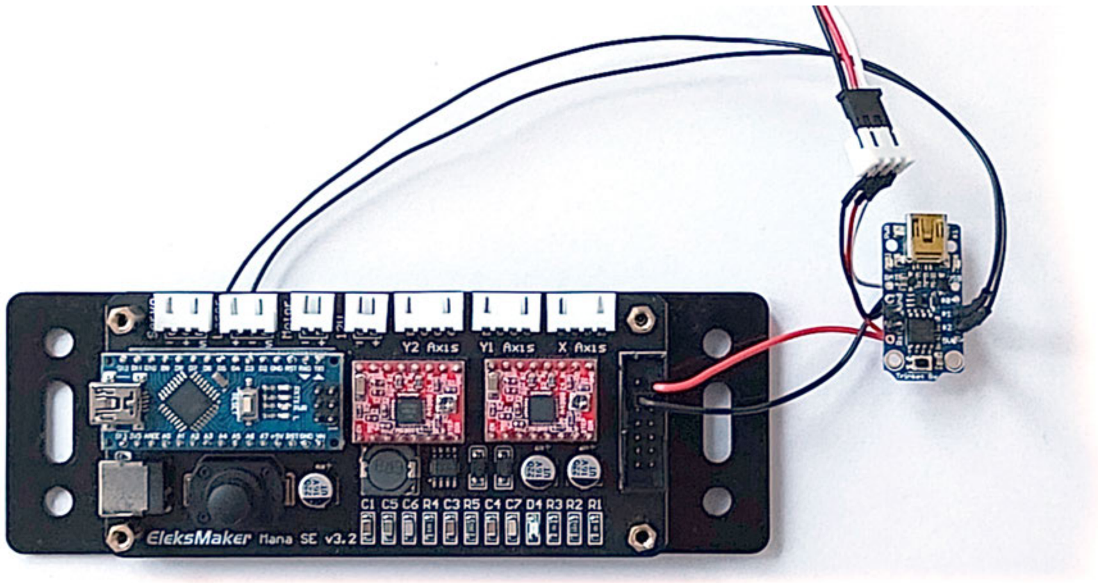


Fig. 23. EleksMana SE v3.2 control board with additional Trinket board as an early prototype.

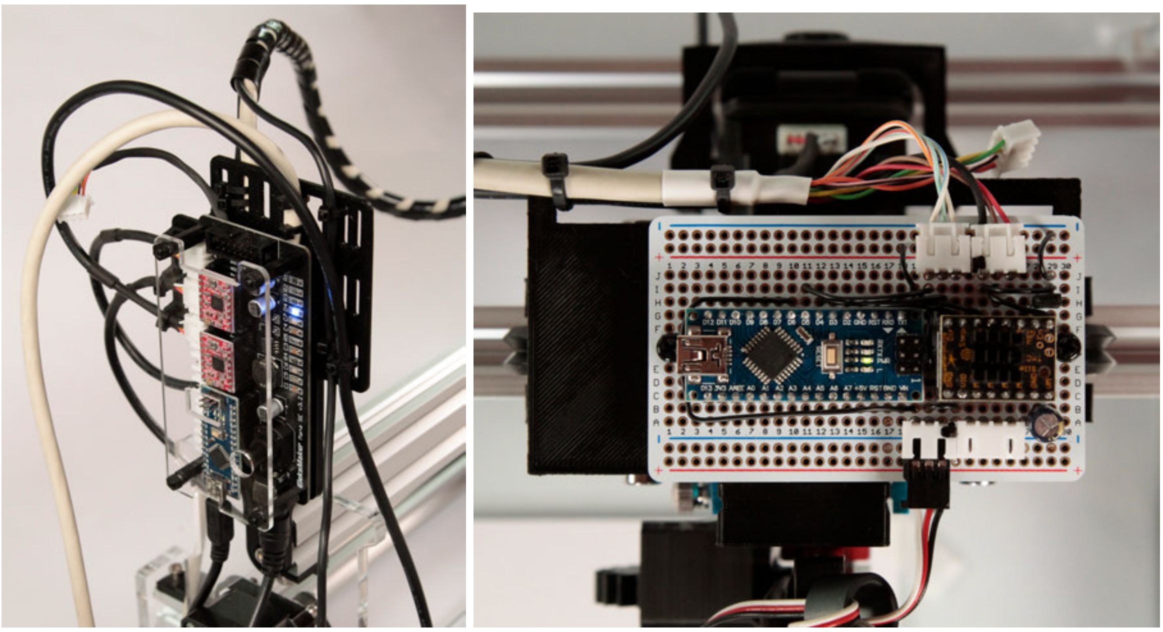


Fig. 24. The finished controller and sub-controller boards.

4.5 General description of the software

Having worked with the Processing programming language and IDE for almost two decades, the decision to use this language to write the required software for driving the pen plotter was clear. The Processing environment was developed to generate visuals (Glassner 2-3). Furthermore, Processing is exceptionally well documented, and a vast amount of libraries are available, including for serial communication via the USB.

The self-developed software for experimenting with the plotter and its advanced pen-lift mechanisms consists of five modules, doing all the steps necessary, from image processing to communication with the plotter's controller.

The **graphical user interface** represents the processed base image or the image generated by an algorithm, which allows for confirmation that an image was processed correctly. This module also allows the user to position the gantry, the pen carriage, and the pen's height before plotting. This can be achieved in real-time by using the keyboard's arrow keys, moving the pen on the X-Y plane, while the PgUp and PgDn keys allow the pen to be lifted or lowered. The increments with which the pen can be moved is set with the number keys from 0,1 mm to 5 mm. Holding down the space bar starts the process of sending the G-code. In addition, the graphical user interface displays the actual position of the pen's tip in real-time.

The image processor module loads a base image from a predefined location and prepares it for the next steps. Namely, it can resize and rotate the image and convert it into grayscale. Finally, the brightness value of every pixel is stored in an array.

The G-code generator module writes the control code, which is the result of a predefined algorithm, into a text file. This module is the most elaborate, and the integrated algorithm is changed to create the desired output.

The file handler module creates an empty G-code file, opens and closes it, and can write to and read from it. The resulting G-code file can also be opened in an external program to visualise the paths of the pen.

Finally, the plotting module handles the communication with the plotter, including sending the G-code instructions via the serial bus, without overloading the buffer of the plotter's controller.

Fig. 25. The graphical user interface of the plotter software.

5 EXPERIMENTATION WITH THE CONVERTED PEN PLOTTER

During and after the building process, experiments utilising the improvements of the plotter were conducted. The collected experiences flowed back into the design of the second version of the pen-lift mechanism. Namely, the lower vertical resolution and the compliance, which resulted in excessive unwanted movement of the pen on the horizontal plane, were considered while designing the second version. In addition, the work on the software progressed simultaneously with the experiments. The resulting drawings confirm that the additions and changes to the plotter are actual improvements as claimed.

5.1 Used material

Watercolour paper was used as the drawing medium. The heavy paper can withstand brush strokes, especially when damp from the ink. In addition, the ink is less likely to print through the thick paper.

Early tests have shown that the Pentel Pocket Brush is well suited for plotting. The pen has a conical brush tip, and its bristles are soft while retaining their shape. The ink is pigmented and resistant to water and light as soon as dry (Pentel). The ink is fed from replaceable cartridges housed inside the pen's body.

5.2 Drawings

While many drawings were made utilising the experimental pen plotter, ten were chosen, illustrating the progress of the work.

The drawings shown below can also be found in the appendix in their original size.

Drawing No 1

Black ink on watercolour paper, 100 mm x 75 mm, 2021

Drawing No 1 is the first plot utilising the new pen-lift mechanism version 1 after a few initial tests. The drawing consists of 24 parallel lines, where half were drawn with the pen starting from a low position and moving up and away from the paper, while the second half was drawn with the pen starting in a high position and getting lower. This drawing serves as a proof of concept, showing that it is possible to dynamically change the stroke width by altering the height of the brush pen's tip.

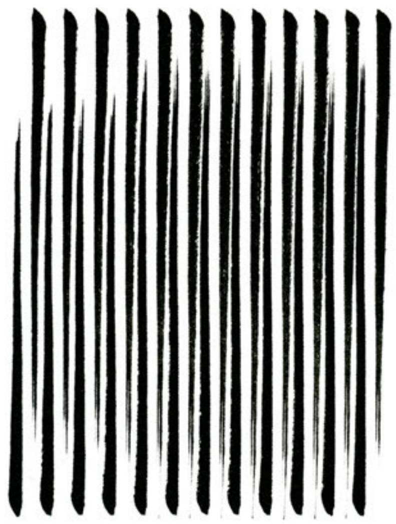


Fig. 26. Drawing No 1.

Drawing No 2

Black ink on watercolour paper, 105 mm x 105 mm, 2021

In drawing No 2, fifty evenly spaced lines are drawn originating from the same point in their centre. The brush's tip barely touches the drawing surface where the lines start. The brush is lowered towards the middle of the lines at a constant pace and then lifted with a variable rate, resulting in differing line lengths.

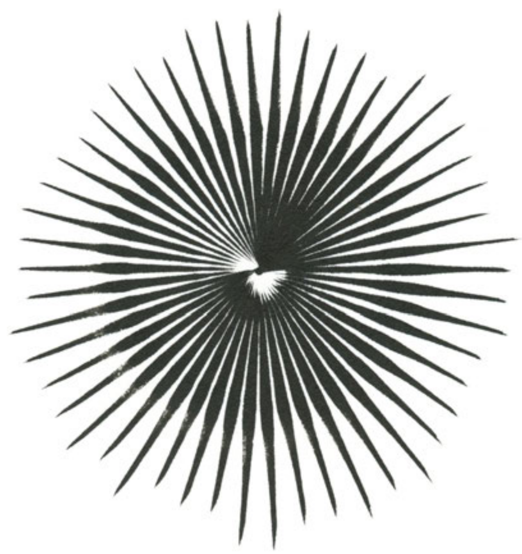


Fig. 27. Drawing No 2.

Drawings No 3 and No 4

Both, black ink on watercolour paper, 100 mm x 100 mm, 2021

Drawing No 3 consists of ten concentric circles, all starting from a different angle. In every circle, the brush is swiftly lowered onto the paper and lifted back up at a random pace during the circular motion, resulting in the variable length.

Drawing No 4 results from running the code of drawing No 3 repeatedly, allowing for the circles to be drawn on top of each other.

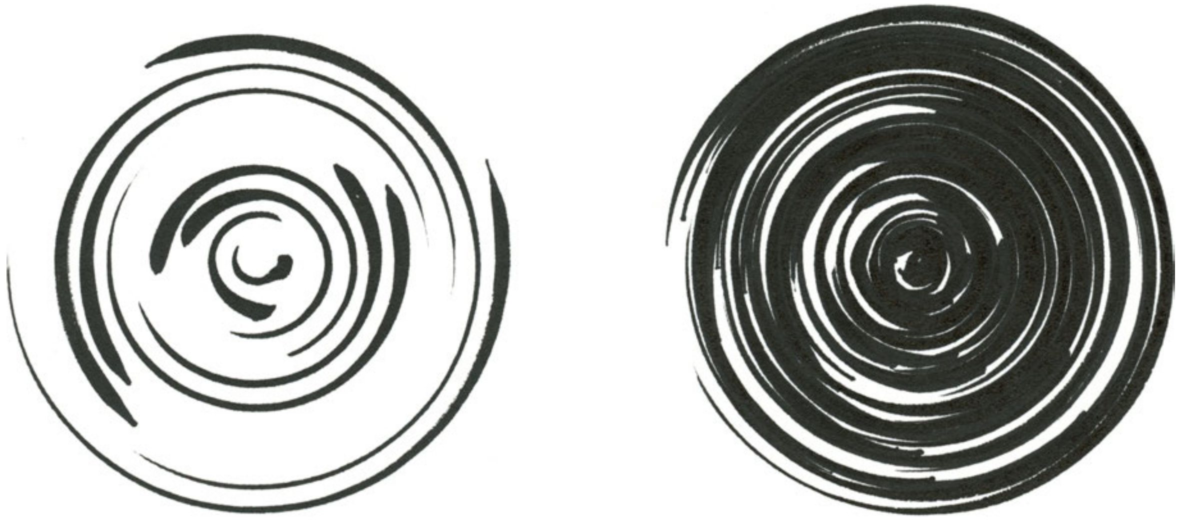


Fig. 28. Drawings No 3 and No 4.

Drawing No 5

Black ink on watercolour paper, 102 mm x 98 mm, 2021

Similar to drawing No 3, No 5 also consists of 10 concentric circles. However, while the starting position is consistently moved by 36°, the pace of the vertical pen movement is tied to the angular motion on the horizontal plane, resulting in a spiral effect.

Fig. 29. Drawing No 5.

Drawings No 6 and No 7

No 6, pink Sharpie pen on watercolour paper, 100 mm x 100 mm, 2021

No 7, black ink on watercolour paper, 100 mm x 100 mm, 2021

These two drawings were generated by the same algorithm, randomly arranging line segments. In a second step, the algorithm calculates which segments are connected in order to be able to draw them as continuous lines. Specifically, generating independent line segments separately before they are combined into continuous lines is an essential step for drawing halftone images, such as No 9 and No 10.

The interrupted and not entirely round shape of the circles in No 6 are caused by the excessive play in the first pen-lift mechanism. No 7 is again drawn with a brush pen and ink and serves as a demonstration of the behaviour of the brush's soft tip, especially when compared to drawing No 6.

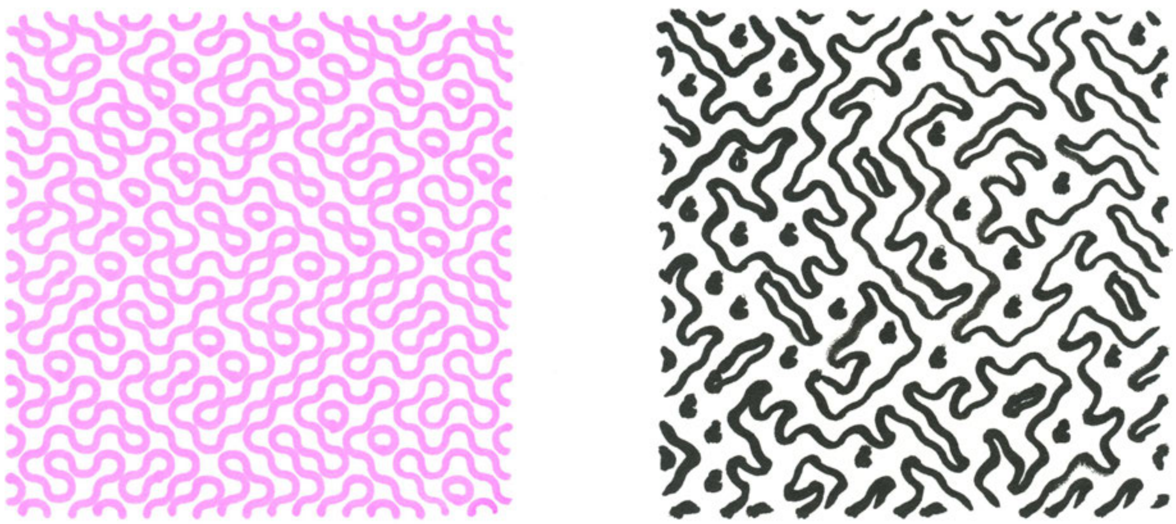


Fig. 30. Drawings No 6 and No 7.

Drawing No 8

Black ink on watercolour paper, 100 mm x 100 mm, 2021

In drawing No 8, 25 parallel lines are used to create a three-dimensional effect. This is the first drawing which displays the potential to use this technique for halftone images.

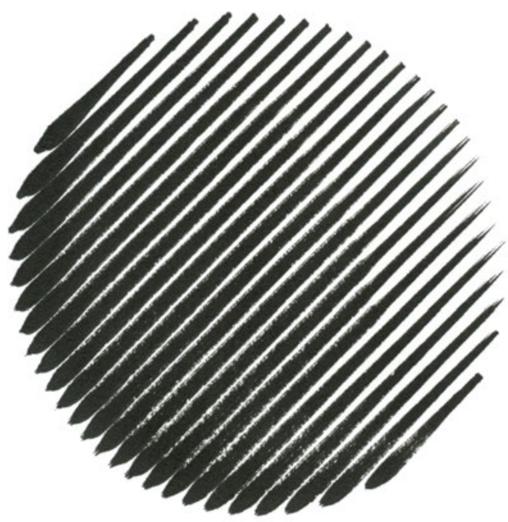


Fig. 31. Drawing No 8.

Drawing No 9

All, black ink on watercolour paper, 100 mm x 100 mm, 2021

These are the first drawings made with the second version of the pen-lift mechanisms, allowing for more control over the height of the brush and subsequently of the amount of ink transferred to the paper. The same control code, generated on the base of the photograph below, was used to draw the three different pictures while the pen was set at a different height each time.

Fig. 32. Photograph and variations of Drawing No 9.

Drawing No 10

Self-portrait, black ink on watercolour paper, 100 mm x 100 mm, 2021

The drawing No 10 is a self-portrait, which is based on the same algorithm as the previous drawing: A base image is converted to grayscale and scaled down to a resolution of 50 x 50 pixels. Subsequently, the lightness values of each pixel are stored in an array and replaced by a diagonal line segment, including the lightness value of the underlying pixel converted to Z-values. Finally, the resulting 2500 line segments are combined into 99 parallel lines, running diagonally from bottom-left to top-right.

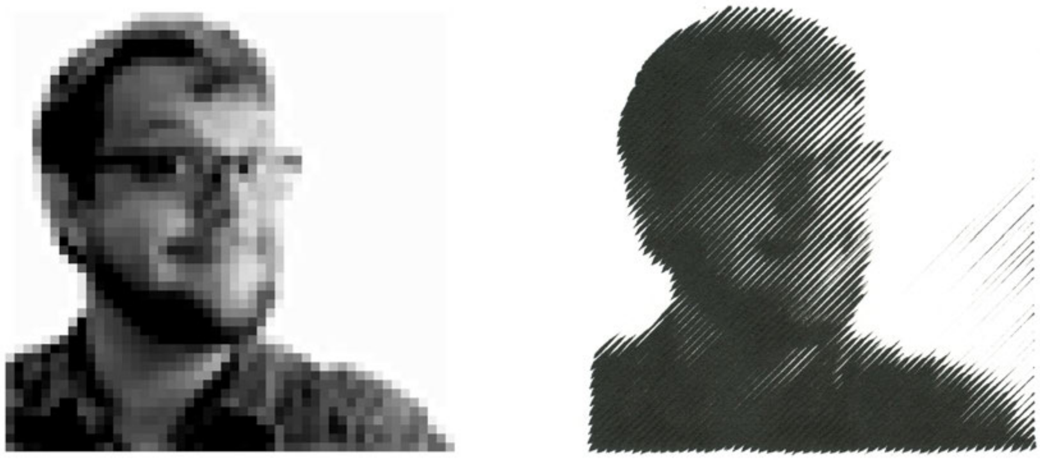


Fig. 33. Pixelated photograph and Drawing No 10.

5.3 Occurring problems during the drawing process

The experimentation utilising the experimental plotter for drawing with brush and ink was challenging in some unforeseen ways. The ink tended to drip from the brush or collect as drops on the brush's tip, resulting in unwanted black blobs on the drawing. It was good practice to draw a line outside the drawing area to wipe the brush before beginning the actual drawing.

Another crucial factor for a successful drawing was to set the brush at the correct height before drawing. The three versions of drawing No 9 show the influence of the height on the resulting saturation.

In the beginning, the dry watercolour paper was taped down onto a glass plate to prevent it from moving. However, the amount of ink transferred onto the paper, especially in areas with dense coverage, led to the buckling of the paper. The buckling results from excess moisture being wicked into the paper's fibres, causing them to extend in length. Naturally, it is impossible to control the height of the pen in relation to the paper if the paper's surface is not flat. Literature about drawing and painting techniques suggests that the paper should be mounted onto a board. This is achieved by wetting the paper, attaching it to a surface with suitable tape, and drying it before use (Magnus 105-106). This method was not very practicable for these experiments, especially considering the potential for plots to fail. The solution was to treat the glass plate with a spray adhesive similar to the glue on sticky notes. After the adhesive dried, it was possible to stick down the paper, which stayed bonded to the glass during the plotting process. The paper could then be removed without any glue residue left on it.

However, the most common failure sources were bugs in the written algorithms, which often needed to be revised countless times.

6 VERIFICATION OF THE RESULTS

The main objective of this research was to build an experimental pen plotter allowing for additional creative possibilities. The focus was, in particular, on gaining the ability to draw lines with dynamically changing stroke weights. The results of this research were verified by the experiments conducted with the pen plotter and the resulting drawings.

6.1 Evaluation of the employed hardware approach

While it is possible to attach a pen to a 3D printer, a CNC mill, a CNC router or an industrial robot arm to get similar results, neither of these were designed to be used as a pen plotter. CNC machines are inherently heavy and expensive. However, many of them would permit to be used as or converted to pen plotters as long as the usable horizontal area to plot on is big enough. In addition to the usual small print bed, the 3D printer has a comparingly slow-moving Z-axis, which results in long idle times for the pen to be lifted and lowered. Nevertheless, it is not wrong to use any suitable means to get into the interesting world of pen plotting.

Concerning the layout of the experimental plotter, the used EleksMaker EleksLaser-A3 Pro has proven to be a good choice. The sturdy frame and the gantry design have advantages over the horizontal T-bot gantry plotters such as the AxiDraw. Especially the ability to add considerable weight to the pen carriage while maintaining a steady distance to the drawing surface. Also, the two motors driving the gantry have enough power to move the additional weight, including the sub-controller board, the pen-lift mechanisms, and the added camera.

Both pen-lift mechanisms have their own strength. While the first version, driven by a servo motor, offers 65 mm of stroke, it can lift a brush high enough to clear the walls of a water container or ink well. However, it is not as accurate as desired for some ink brush pen experiments. Consequently, a second pen-lift mechanism offering more resolution, accuracy and precision was designed and built. Yet, this second version has only a stroke of 12 mm.

Mounting a camera on the pen carriage allows documenting the plotting process from an interesting angle. Mainly when many artists rely on social media for their marketing, recording and editing appealing videos has become more critical. Furthermore, this allows for promoting the performative character of the plotting process with others.

In conclusion, the developed hardware, including the sub-controller, has proven to work reliably. Specifically, the pen-lift mechanisms provide additional creative possibilities, as is the main objective of this research. Furthermore, swapping between the two mechanisms allows for experimenting with different media. On the one hand, the drawing implement can be lifted over high obstacles, while the writing implement can be moved swiftly and with high accuracy and precision on the other hand.

6.2 Evaluation of the employed software approach

The non-conventional hardware can only be used with a custom software solution to generate the necessary control code. The approach to developing modular software supports the experimental character of this research. While there are tasks, which need to be executed, regardless of the visual output, clear interfaces to the modules handling those tasks were defined. The resulting transparent structure made the development process more efficient. As the plotted results suggest, the developed software can generate control code that allows utilising the two versions of the pen-lift mechanisms. In addition, the code written for the sub-controller made it possible to overcome the insufficient resolution of the servo signal generated by the main controller.

6.3 Evaluation of the resulting drawings

The drawings made during this research illustrate the potential of the experimental pen plotter as a creative tool. Some of the drawings are based on algorithms generating lines with varying stroke weights. Others are halftone images based on photographs and drawn as lines with dynamically changing thickness.

6.4 Similar works done by other members of the plotter community

Two authors of projects with similar approaches were willing to share their experiences in interviews conducted in late April 2022. These interviews offer a small insight into how other pen plotter community members are approaching the problem of dynamically controlling the pen-lift mechanism with precision and accuracy.

Experiments with variable pen height by Joshua Schachter

Joshua Schachter explains that he has built several pen plotters to this date and uses them as a creative tool. Specifically, during the spring and summer of 2020, he conducted experiments with ink brushes and paint pens that he mounted to the Z-axis of his drawing robot. The ability to dynamically influence the height of the Z-axis allows him to control the height of a brush or the pressure on a pen, affecting the appearance of the resulting stroke.

One of his early experiments was to draw a simplified version of the Chinese brushstroke shù. The stroke is performed by four separate motions on the horizontal plane, while the brush performs a down- and upward movement. He generated the necessary G-code based on a CAD model and added the commands for the Z-axis by hand.

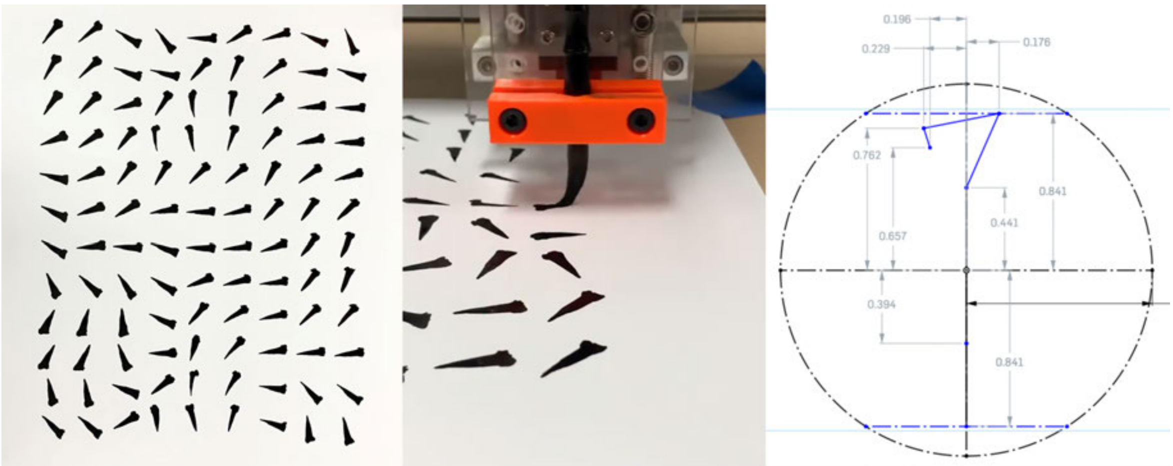


Fig. 34. Chinese brushstroke drawn with a complex motion and CAD model thereof.

In another experiment, Joshua Schachter utilised paint pens, where the pens' motions describe parallel lines, in black on one axis and in red on the other. The height of the pens is controlled by the result of the cosine of Perlin noise. His algorithm generated the G-code for this drawing.

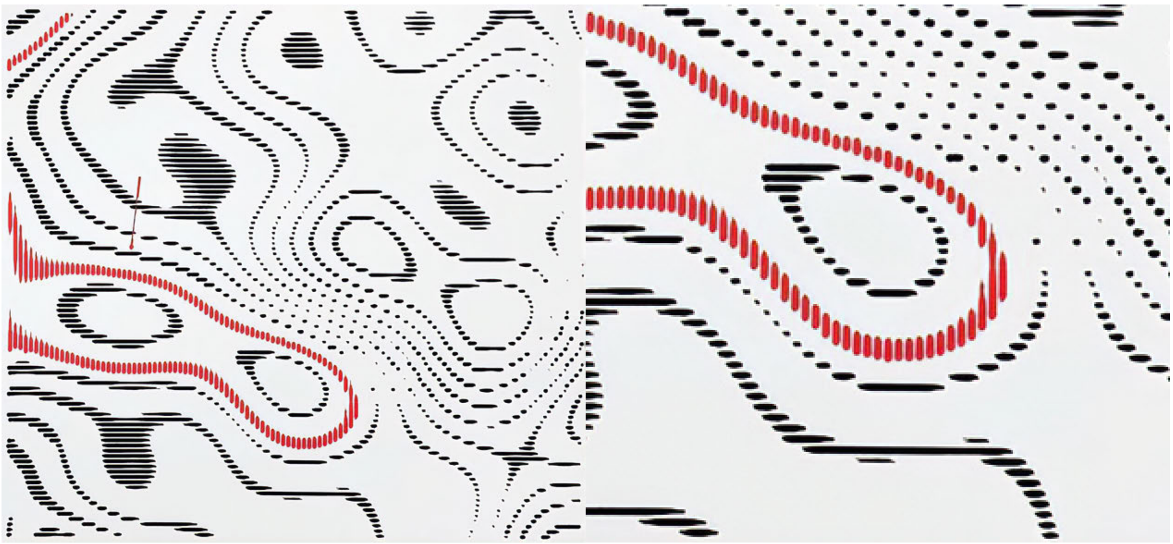


Fig. 35. Experiment with variable pressure on paint pens and detail thereof.

Further, he explains that the lack of control over the unpredictable bristles of a brush was why he did not further pursue his experimentation with brushes (Schachter).

Joshua Schachter's drawing robot, whose mechanical design is based on the frame of a sturdy and precise CNC router, invites experimentation. Specifically, the weight capacity of the gantry allows him to add not only writing and drawing implements but also extruders and other experimental means to apply paint, ink, and dye on paper. In addition, he makes good use of his expertise in software development, allowing him to write algorithms generating the code necessary to control the vertical axis. The main difference between his pen-lift mechanism and the mechanisms designed for this research is that his design is mechanically compliant: The pen stops its downward movement as soon as the tip touches the drawing surface while the pressure on the pen increases.

Haiku by Mattia Fanu Ceruti

Fanu Ceruti built an AxiDraw clone controlled by a GRBL control board. He explains that initial experiments with a pen-lift mechanism utilising servos have shown that he could not achieve a satisfactory resolution with which he could control the pen height. Consequently, he built a pen-lift mechanism driven by a stepper motor, mounted to the frame of the plotter, actuating the mechanism with a Bowden cable.

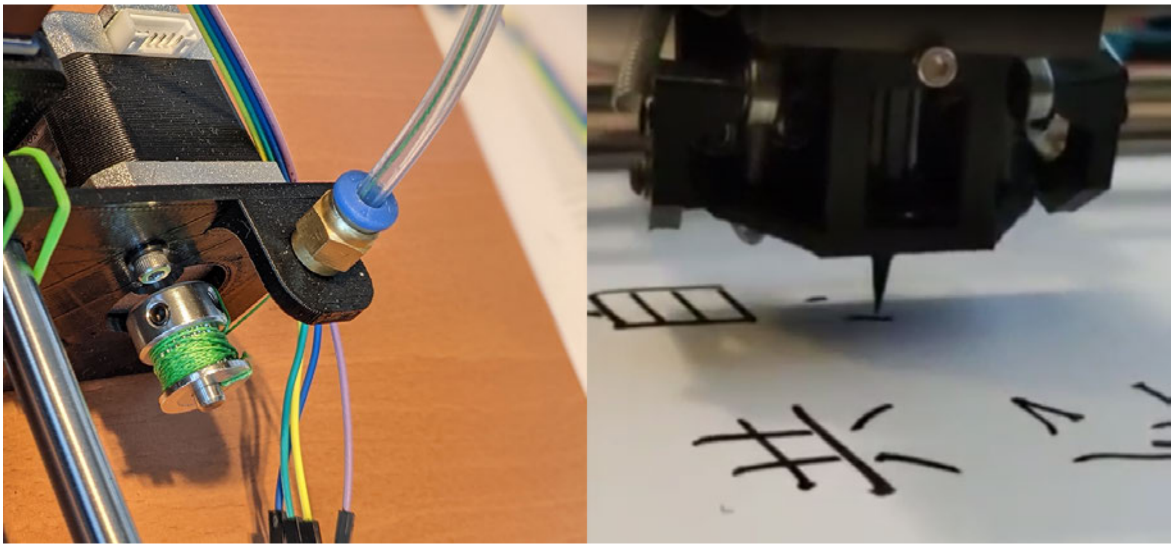


Fig. 36. The pen-lift mechanism is operated using a Bowden tube.

This design allowed Fanu Ceruti to control the height of the pen with a high enough resolution to control the line weight when using brush pens with conical tips. His fascination with the Japanese language and its logographic characters, kanji, led him to the question of whether it would be possible to use his pen plotter to write a haiku.

Fanu Ceruti clarifies that it was essential to keep the sequence and direction of the lines. He downloaded the kanji character as an SVG containing the necessary vectors and converted them into G-code. He had to edit the G-code manually to add the missing commands concerning the height of the brush pen commands (Ceruti).

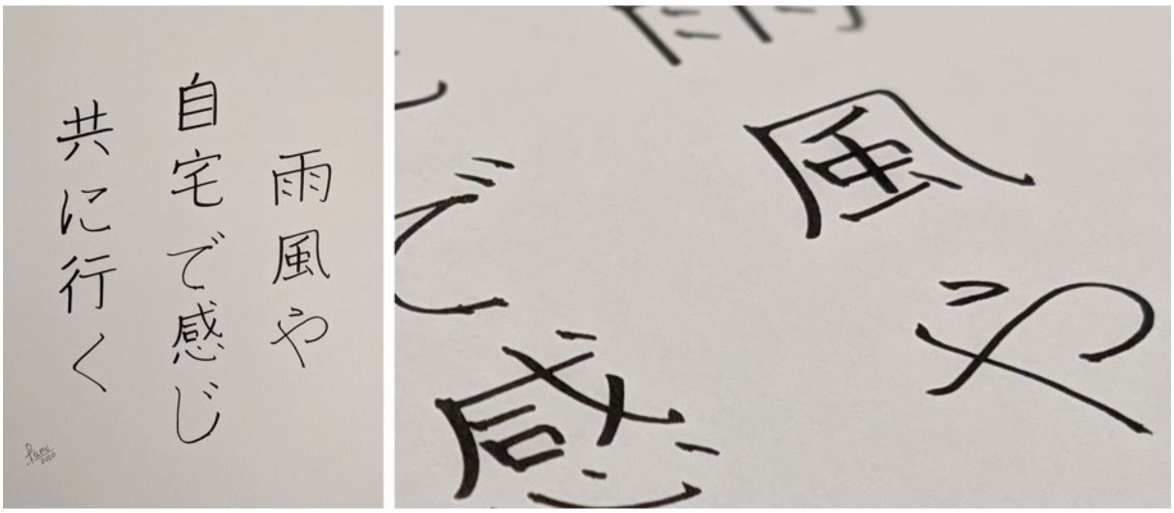


Fig. 37. Haiku by Fanu Ceruti, 2020 and detail thereof.

The approach of Fanu Ceruti, using a GRBL controller and designing a pen-lift mechanism that controls the height of a brush pen in a sufficient resolution, is similar to the method in this research. Hand-editing the G-code allowed him to create this haiku, which demonstrates the possibilities of a pen plotter with a nonconventional way to control the pen on the Z-axis.

6.5 Personal Outlook

Theoretical research

I would like to write more about the early days when pen plotters were used in algorithmic art. Specifically, the practicalities and their implications for the artistic output interest me. Furthermore, it seems that pen plotters are being overlooked in media history, and it might also be interesting to extend my research in that direction.

Practical research

I am looking forward to using the experimental pen plotter to generate more creative output. Especially, multicolour plots intrigue me. I am also interested in researching the contrast between the exactness of the machine and the organic nature of ink brush drawings. Unfortunately, I did not have much time to test some of the pen plotting devices, attachments, and supplies I collected in the past year, and I am eager to try these out. In addition, I would like to systematically test different drawing implements and document how they can be used with the experimental plotter.

Concerning the experimental plotter, I will develop a third version of the pen-lift mechanism, allowing for mechanical compliance and exploring ways to reliably and predictably influence the resulting pen pressure.

6.6 Personal Conclusion

Finding a topic for my master's thesis was not easy. However, after laying my hands on a pen plotter for the first time, I got intrigued. At the time, I did not yet understand the magnitude of their impact on algorithmic art. Still, it seemed to be a topic cut out for me: Improving a tool that I can use for my creative output while applying technical knowledge was ideal. I have no regrets about my choice, and I can honestly say that I enjoyed the process of building and using the experimental plotter as much as writing this paper.

As a younger student, 20 years ago, I did not know what a luxury it is to have sufficient time to dwell over a topic leading me down the figurative rabbit hole. I conducted this research with much enthusiasm. I was blessed with many engaging and kind encounters, often surprising me, how willingly knowledge was shared in the plotter community and the general readiness to help. The voiced interest in the outcome of this thesis kept me motivated. Thus, I am happy to be able to share a part of the gained insight with anyone interested, and I hope this paper will serve as an encouragement to pursue similar experiments. Pen plotters are as captivating today as they were six decades ago. It seems that there truly is something magical about these drawing robots.

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FIGURES

TABLES

APPENDICES

Expert interviews and personal correspondence

Herbert Bruderer (herbert.bruderer@bluewin.ch; bruderer@retired.ethz.ch) is a retired lecturer in the Department of Computer Science at ETH Zurich, a historian of technology, and author of *Milestones in Analog and Digital Computing*.

Email from Herbert Bruderer concerning the involvement of the Swiss Contraves AG in developing pen plotters. Received by Martin Bircher, 18 Apr. 2022.

> Die Contraves hatte einen Koordinatografen von der Firma Haag-Streit AG (heute in Köniz BE) übernommen und zum Coragraphnen weiterentwickelt (vgl. Meilensteine, Band 2, Seite 210f.). Diese Koordinatografen kommen in Band 1, Seiten 233f. vor.

Mattia Fanu Ceruti is an experienced code artisan with a history of working in the internet industry. His passion for travelling and love of foreign languages reflects in his art, as does his fascination with technology.

A personal interview with Fanu Ceruti was conducted over Discord video call by Martin Bircher, 21 Apr. 2022. Duration: 70 minutes. The interview has been recorded, and Fanu Ceruti confirmed the correctness of the citations on 9 May 2022.
The interview was about his work utilising a pen plotter with a self-built advanced pen-lift mechanism. The conversation focused on specific experiments, where he replicated kanji writing with a brush pen.

Lenore Edman is known as the "fairy godmother of making". She is co-founder of Evil Mad Scientist Laboratories, manufacturer of the popular AxiDraw pen plotter, and she is very involved in the plotter community and the maker movement.

E-mail interview with Lenore Edman conducted by Martin Bircher, 13 Dec. 2021.

How do you perceive the development in interest in pen plotters since the introduction of AxiDraw in 2016?

> Prior to the arrival of AxiDraw, plotters tended to be vintage, DIY, or custom purpose. Vintage plotters have limitations in hardware, setup, and workability. DIY ones often have a less-polished software and hardware experience. Custom purpose plotters often have barriers to use for other purposes. So those who were working with plotters prior to AxiDraw tended to be willing to overcome barriers to entry. AxiDraw was designed to be flexible and work on any platform (Mac, Windows, Linux) and with a variety of pen types, and to draw on any surface, which dramatically changed the environment for those using plotters for creative purposes.

How would you explain the revival of pen plotters in generative art and design?

> Everything old is new again. Pen plotters have been used for art since their advent in the mid-20th century. As digital fabrication tools (laser cutters, vinyl cutters, 3D printers, CNC routers, etc) have become more accessible with the growth of the maker movement, the tools for designing for them have also developed and become more accessible. A pen plotter is a tool with a low barrier to entry in terms of material costs and workshop risk, so has a solid place in the toolset for digital fabrication/design/art education.

What role does AxiDraw play in this revival?

> Because AxiDraw is able to work with a wide variety of tools and materials, it has a broad appeal to artists who push the boundaries of what a tool can be used for. Similarly, because the software is open source and well

documented, artists are able to use it in unanticipated ways and to create their own software tools to work with it. The ability to use archival papers and inks cannot be understated as a way to bring digital art into the physical world.

Did you expect AxiDraw to be as popular as it is before its introduction?

No, we were quite surprised by the demand for it. And while the generative art community is one of the more vocal advocates of AxiDraw, they are by no means the largest. We were particularly surprised by the adoption from folks using it for handwriting-like applications who make up the bulk of AxiDraw users. Generative artists may be our favorite group, though!

A personal follow-up interview with Lenore Edman was conducted over Google Meet by Martin Bircher on 13 Jan. 2022. Duration: 45 minutes. The interview has been recorded, and Lenore Edman confirmed the correctness of the citations on 27 Apr. 2022.

Interview Questions:

- Is the success of AxiDraw in the art community more due to its hard or its software?
- What things utilizing AxiDraws have fascinated you the most?
- Can you tell a bit about your customers utilising the AxiDraw in handwriting-like applications?
- Do you think, considering handwriting-like applications, EMS is the biggest manufacturer of professional pen plotters in the market?
- Have we already reached the merit of the pen plotting revival?
- Do you think that the pandemic is influencing the popularity of pen plotters?
- What do you think is the fascination with the plotting process?
- How are the results differing from, let’s say, high-quality inkjet printing?
- Are you using a pen plotter yourself?
- Which other platforms besides #plottertwitter and drawingbots on discord are popular in the pen plotter community?

- How would you describe the pen plotter community?
- Who are its typical members?

The Discord member **Jason** is an expert in plotters from the 1980s and 1990s. Especially with his vast knowledge about their control language and communication protocol, he is actively helping community members get vintage plotters connected to modern-day computers to give them a second life. In addition, Jason designs hardware to make the use of vintage pen plotters more convenient.

A personal interview with Jason was conducted over Discord video call by Martin Bircher, 12 Apr. 2022. Duration: 150 minutes. The interview has been recorded, and Jason confirmed the correctness of the citations on 27 Apr. 2022.
Interview Questions:

- How did you perceive the recent revival of pen plotters?
- Have we already reached the merit of the pen plotter revival?
- Why do you think the revival happened?
- Do you think that the pandemic is influencing the popularity of pen plotters?
- You are very active in the plotter community and often ready to help with advice, especially concerning vintage plotting equipment. What motivates you?
- How do you perceive the plotting community?
- What do you think is the fascination with the plotting process?

Message from Jason to Martin Bircher about the roles of Hewlett-Packard and the Japanese pen plotter manufacturers. Discord, 19 Apr. 2022.

> It may be worth noting that the Japanese never really held a notable stake in the market and only really became a numerically proportionally large contributor to the pen plotter market for a very short period after HP left the market in the 90s and moved over to electrostatic, laser, and inkjet. This left the market open for the other manufacturers although most did not continue

for long with pen plotters. Roland and co. diversified the machines by modifying and developing them towards being used in the vinyl cutter, something that HP never did.

It is interesting to talk about the time before HP entered the market with the first "paper pusher" models that completely changed everything. This period was dominated by flatbed style plotters made by mostly European companies. These were very specialised machines and were unaffordable to the average company. Although still expensive back in the day, the change to comparatively cheap paper pusher machines was HPs great game changer move. To my knowledge, the last places still manufacturing pen plotters today are the Germans, who make plotters to write on labels used in the electrical industry for marking cables and connections.

Windell Oskay is co-founder of Evil Mad Scientist Laboratories, is a hardware design engineer and holds a PhD in Physics. He knows the AxiDraw plotter better than anyone else.

Windell Oskay on how the AxiDraw's design should be classified concerning its mechanical structure. Message to Martin Bircher on Discord, 21 Nov. 2021.

I think the best description would be a horizontal T-bot gantry plotter.

Windell Oskay on the question about the AxiDraw's pen-lift mechanism and the resolution it can be controlled. Message to Martin Bircher on Discord, 1 Apr. 2022.

I really don't have a good answer for that.

The AxiDraw is really a "2.1D" design, with XY motion plus pen lift and lower. It does not have full three-dimensional motion control, and we have never advertised it to.

There is some amount of adjustability in the pen-up and pen-down positions, but there is no calibration nor consistent linear mapping between the controlled positions and the actual Z heights achieved.

> Further, the AxiDraw geometry -- which has the cantilevered arm and no fixed bed -- does not guarantee a consistent pen-over-page height. The Z stage design is specifically designed to "float", resting the pen on the drawing substrate. This generally takes out issues due to variable pen-over-page height, and additionally allows the machine to work with surfaces that have fairly complex geometry (within the compliance range).

Joshua Schachter is an entrepreneur and angel investor in Silicon Valley. The founder of del.icio.us has a passion for building robots that draw. His numerous experiments involving different ways to bring ink or paint on paper are testimony to his urge to innovate.

A personal interview with Joshua Schachter was conducted over Google Meet by Martin Bircher, 27 Apr. 2022. Duration: 60 minutes. The interview has been recorded, and Joshua Schachter confirmed the correctness of the citations on 11 May 2022. The interview was about his work utilising pen plotters. The conversation focused on specific experiments, where he used brushes and paint pens while dynamically changing the Z-height of the drawing implement.

Maks Surguy is an artist and design technologist who actively supports the plotter community by collecting and publishing knowledge about the topic. In 2018 Maks started with Drawingbots.net, a website with vast information about pen plotter hard- and software. In addition, he created the corresponding drawingbots discord channel, serving as a place where the plotter community can exchange ideas, find solutions, inspiration, and encouragement.

E-mail interview with Maks Surguy conducted by Martin Bircher, 18 Apr. 2022 with follow-up question from 22 Apr. 2022.

Where do you see the reasons for the recent revival of pen plotters?

I think we're entering a new era in computer assisted art. Drop in prices of CNC machines (lasers, 3D printers, 2D machines such as CNC mills, etc) combined with proliferation of free or low cost software for making complicated generative designs for these machines, is enabling artists and engineers all over the world to experiment at the intersection of digital and physical mediums. I believe that with more people being able to afford a pen plotter or build their own, and because pen plotting can be both a fun hobby and a source of income, pen plotters are becoming more popular.

Have we already reached the merit of this revival?

No, I think we're only in the beginning stages. There is still a lot of room for innovation and improvement of tools, machines, processes. We also see more and more multi-purpose tools entering the market, such as laser/3D printer/pen plotter. When the cost of high quality hardware becomes low, and ease of use of software reaches its peak, we will see a "cambrian explosion" in the CNC world, and pen plotting will also benefit from that. There's been a lot of progress, but there's also a lot to be done.

You are very active in the plotter community and often ready to share your vast knowledge and give encouragement. What motivates you?

I think we can always achieve more when we share ideas and work together. In the process of sharing with others, I also learn a whole lot. For example, by starting a plotter-specific Discord, I got to talk to hundreds of like-minded people and learn from them. In my opinion, the process of sharing knowledge is always bi-directional. Also, by encouraging others, I build a bigger community of plotter enthusiasts, and the bigger this community is - the bigger the range of ideas and information I get to be exposed to.

How do you perceive the plotting community?

In my opinion, it's a very unique and open community. In fact, it is so unique and interesting that there's been research into how this community operates and how it shares information. Please look at https://www.youtube.com/watch?v=xqhT-8ElJ68 and relevant paper from 2021 ACM CHI: https://dl.acm.org/doi/10.1145/3411764.3445653

Where do you think lies the fascination with the plotting process?

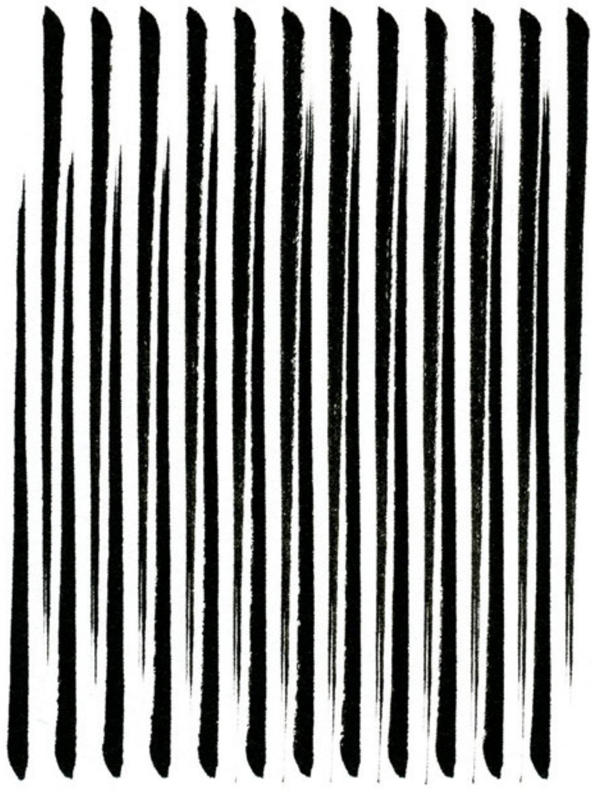
Plotters are robots that draw. Robots are extensions of ourselves, extending our own abilities. Watching robots make things or make art, is something that attracts kids and adults alike. Robots don't care about complexity of the illustration / design, they just execute the commands issued by the operator. Naturally, when we see "superhuman" abilities of drawing robots, we are in awe of their precision and speed. Ability to use a variety of unique combinations of supplies and surfaces for drawing, makes plotting practically unlimited in its potential. Besides inks and papers, there are many alternative uses for plotters. Some people use plotters to grow bacteria in unique patterns, some use them to make patterns in sand, and some others use them to scratch mirrors with unique designs. And we are just scratching the surface!

Follow up question from 21 Apr 2022: Who are the typical pen plotter community members?

In general, I noticed a few patterns:

- tech workers (programmers, developers)
- scientists
- professors
- robotics engineers / students

Drawings in original size and high resolution



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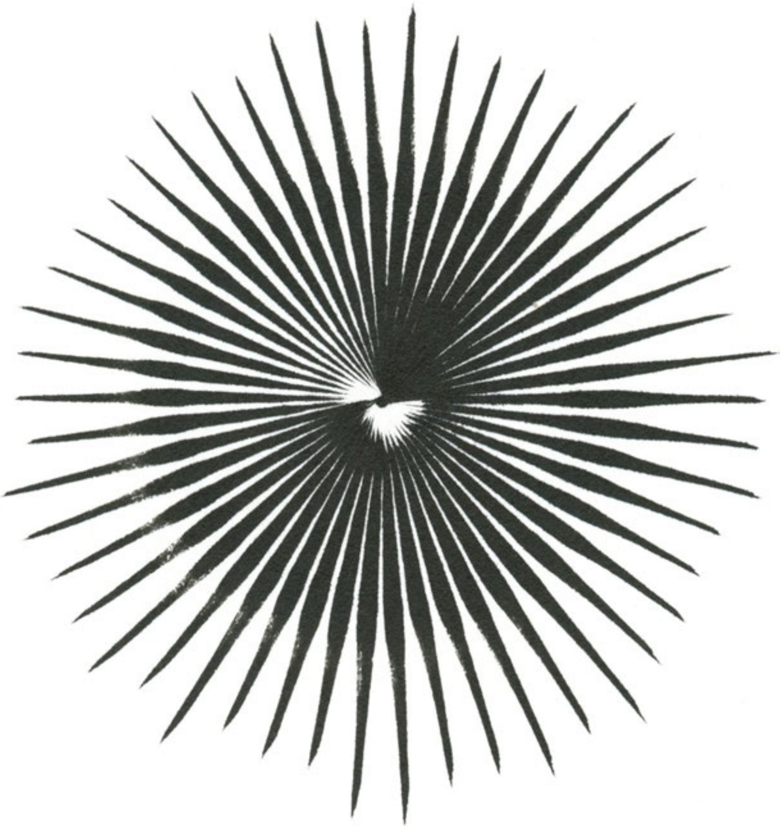
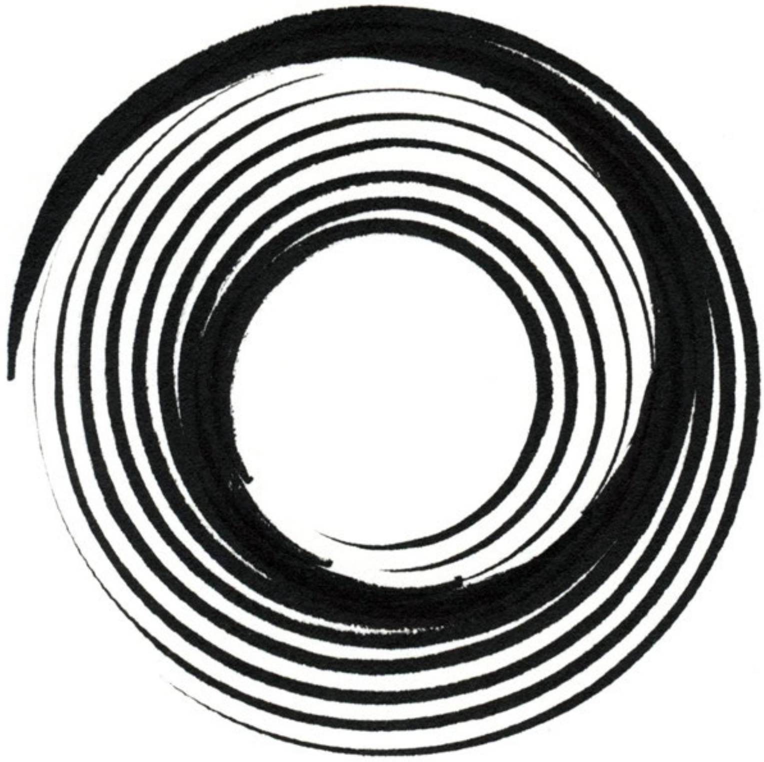


Drawing No 2.

Drawing No 3.

Drawing No 4.



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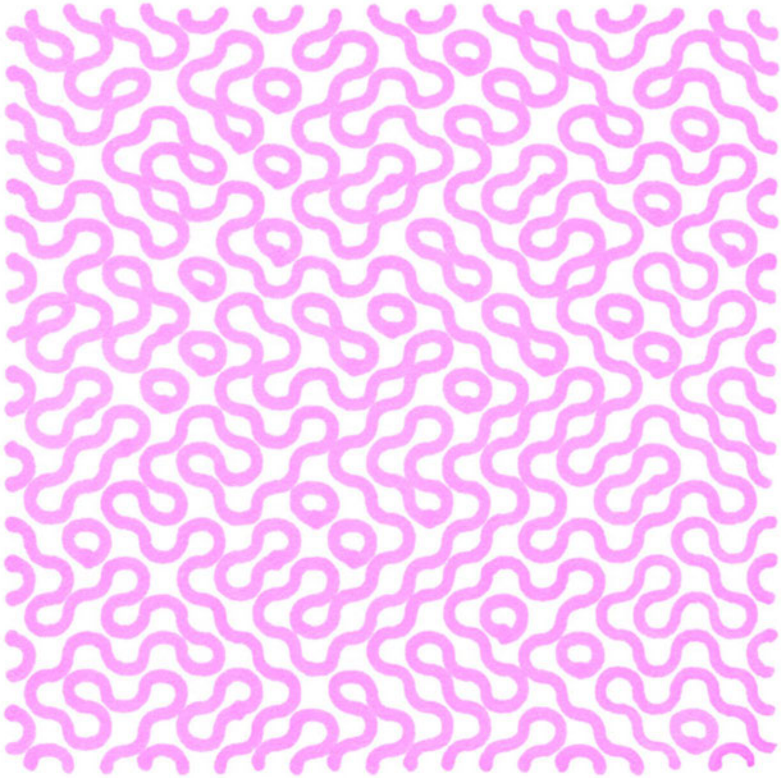

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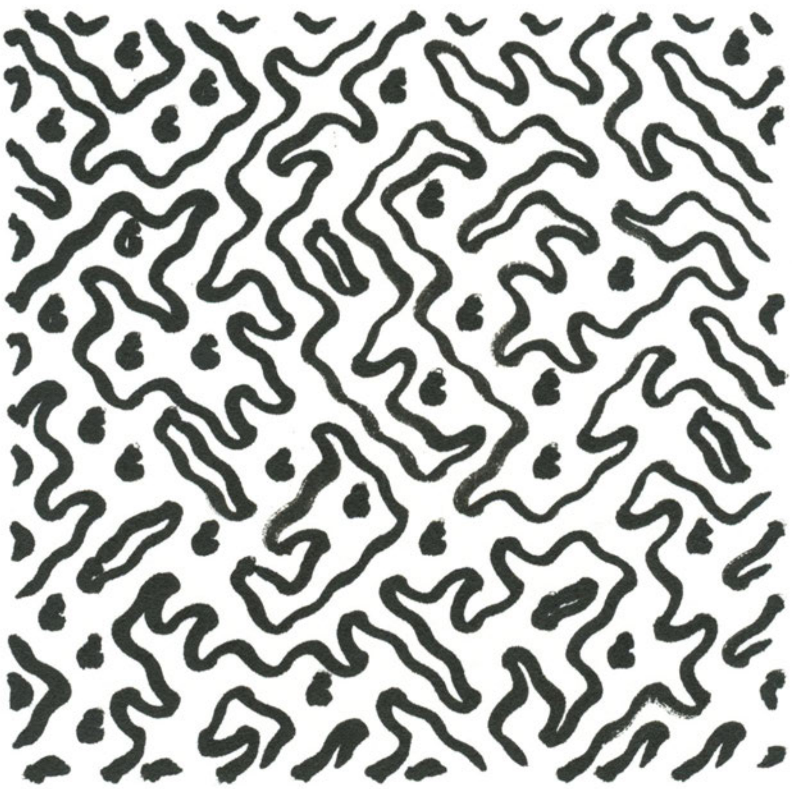

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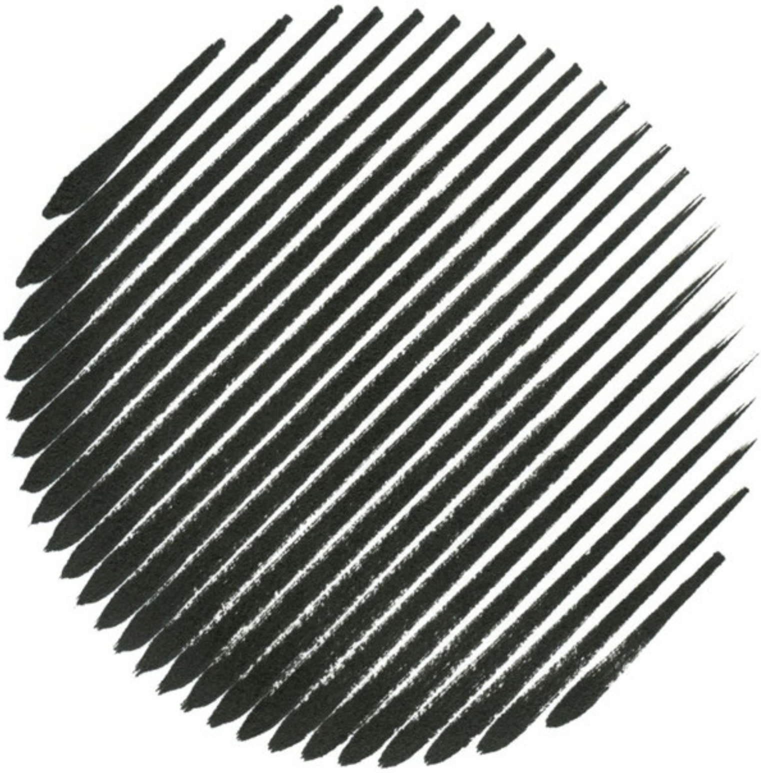
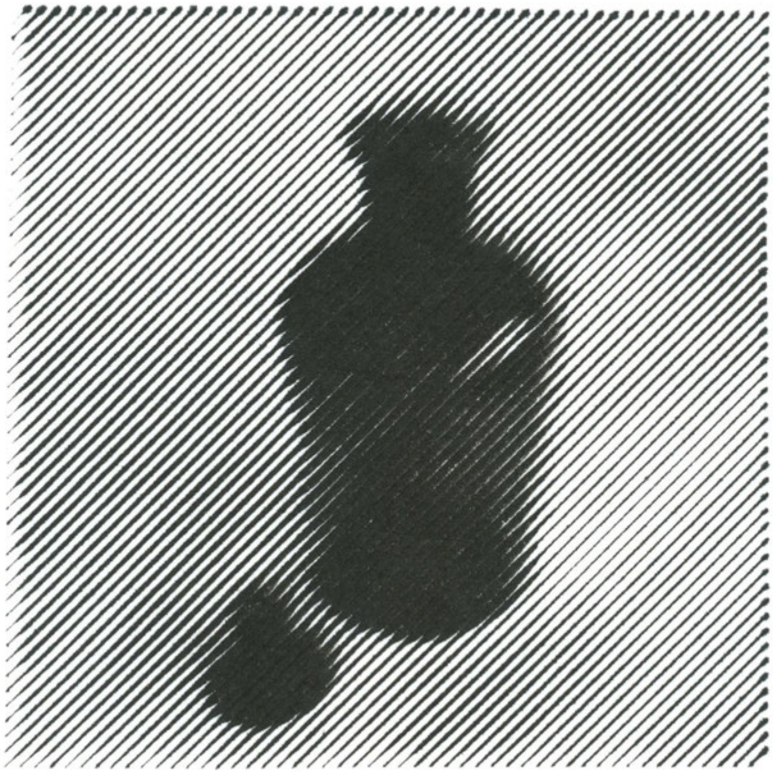
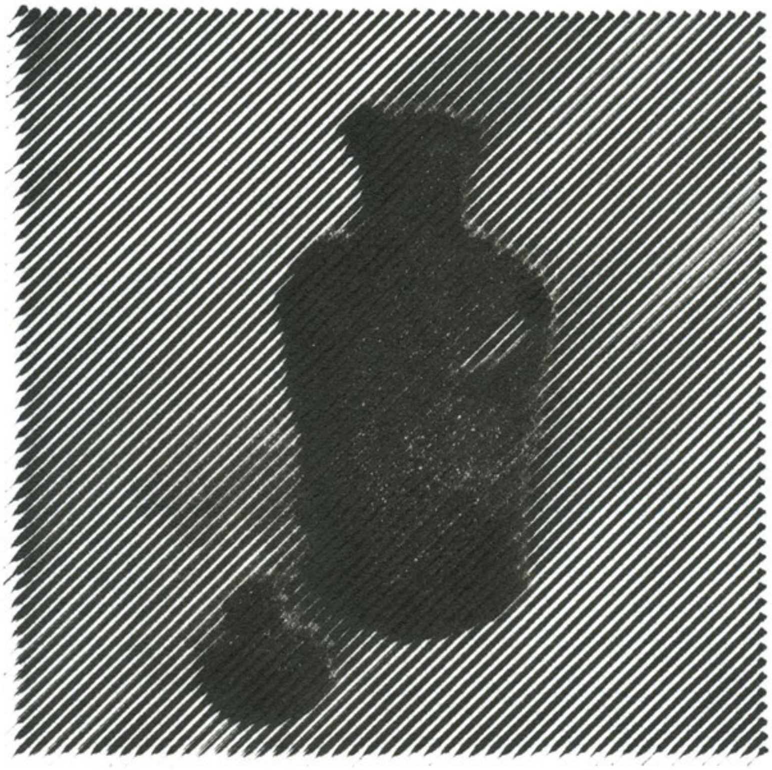


Drawing No 8.



Drawing No 9, light version.



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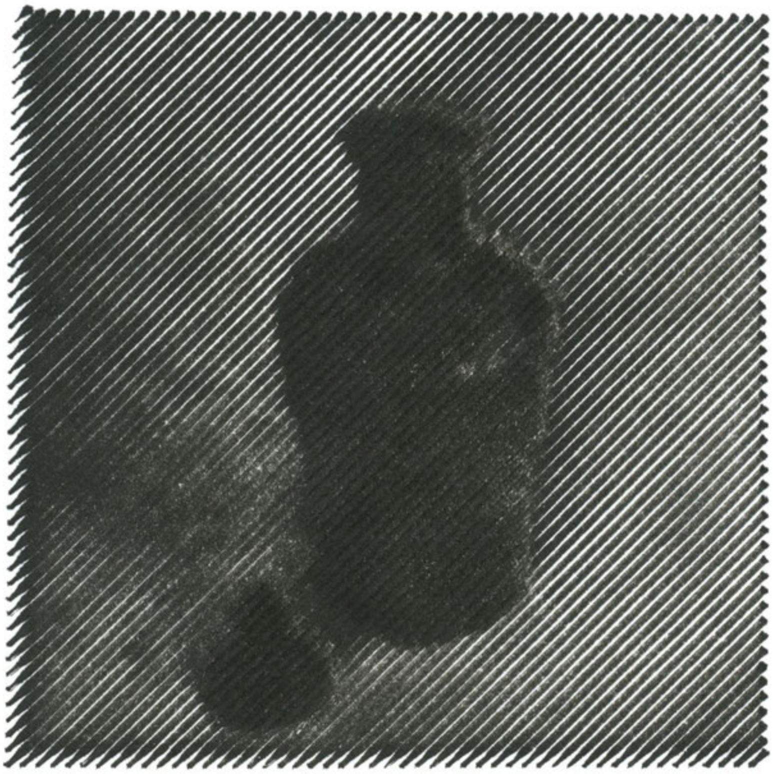
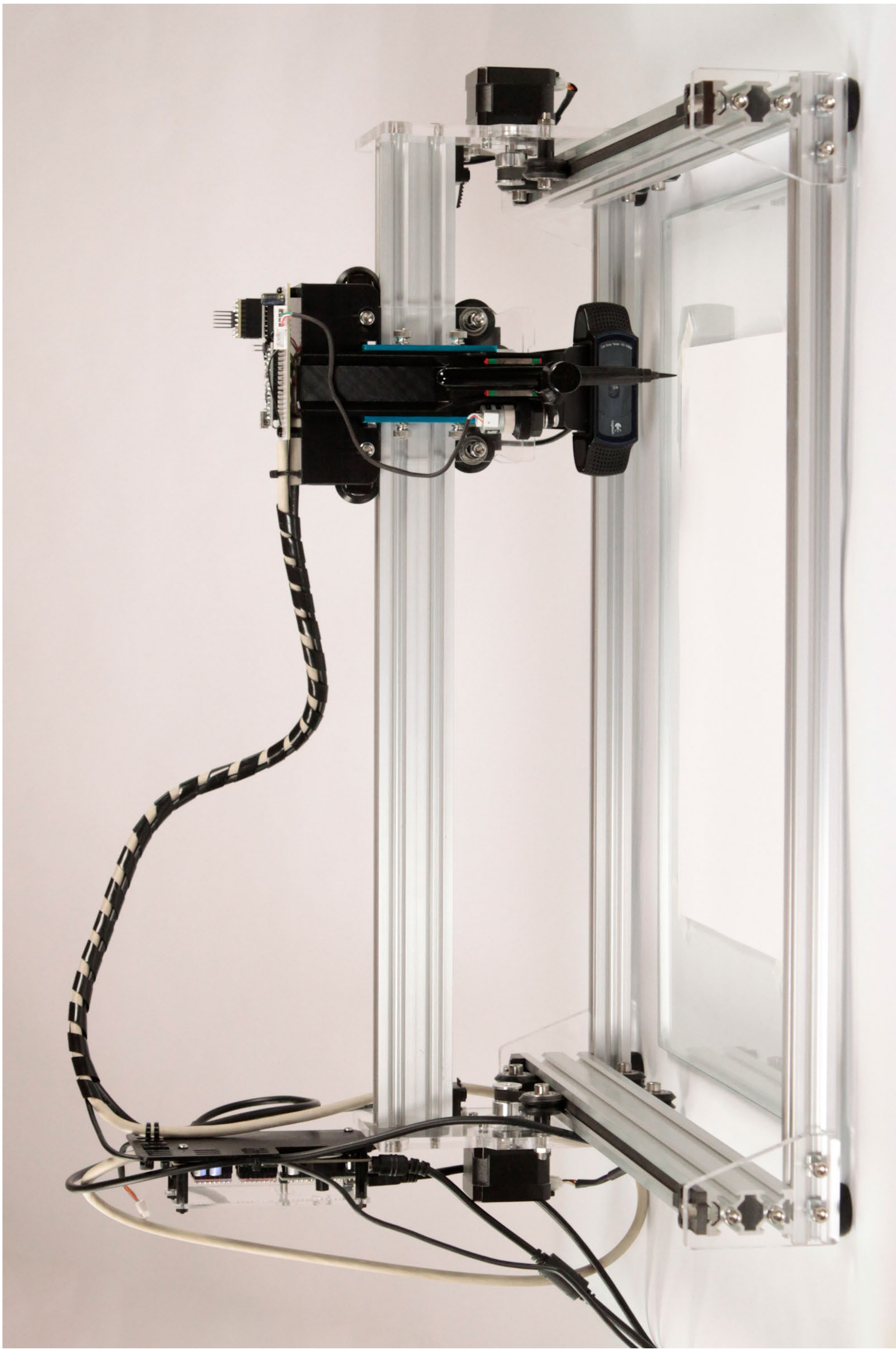


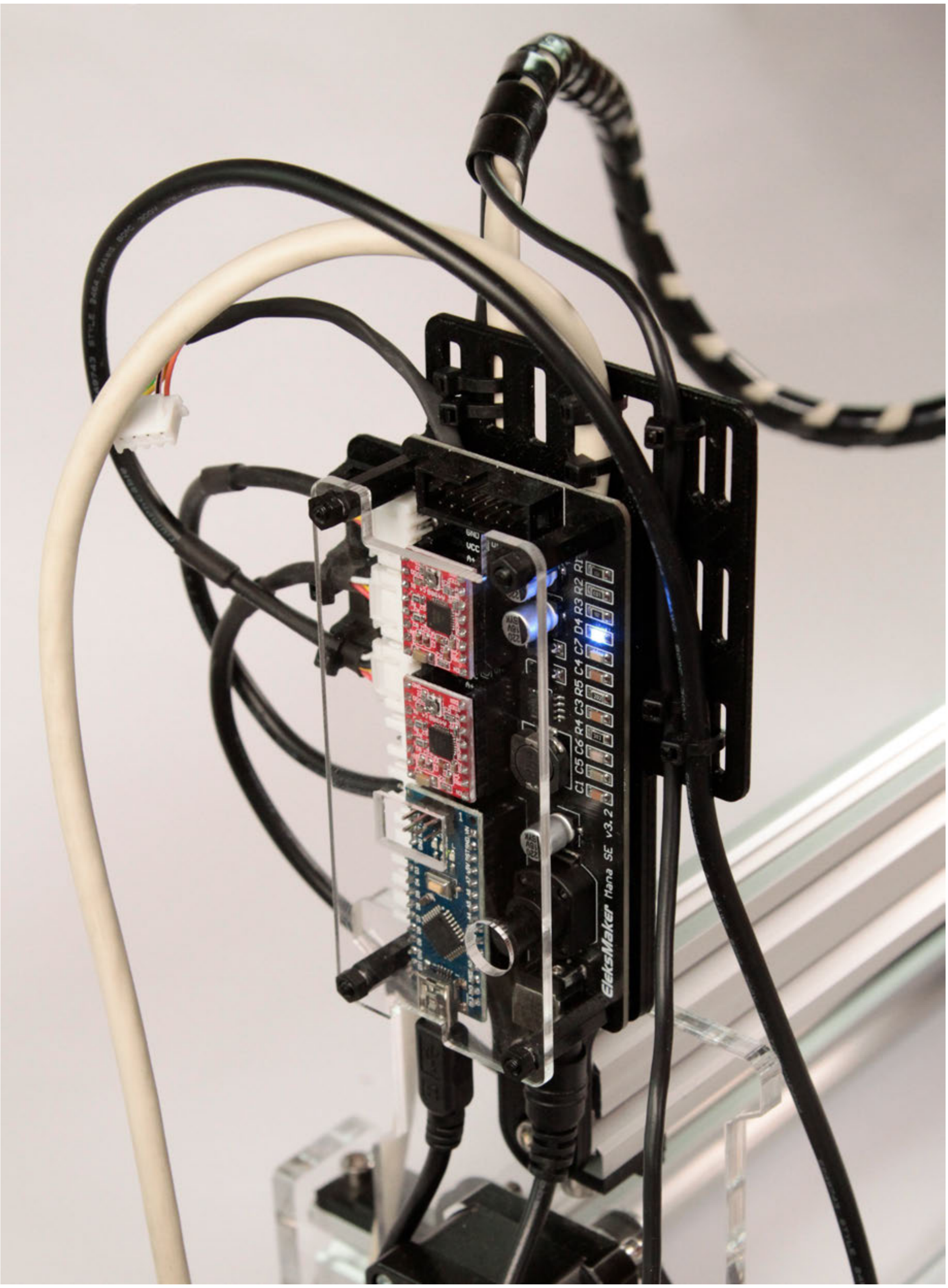
Drawing No 9, dark version.

Drawing No 10.

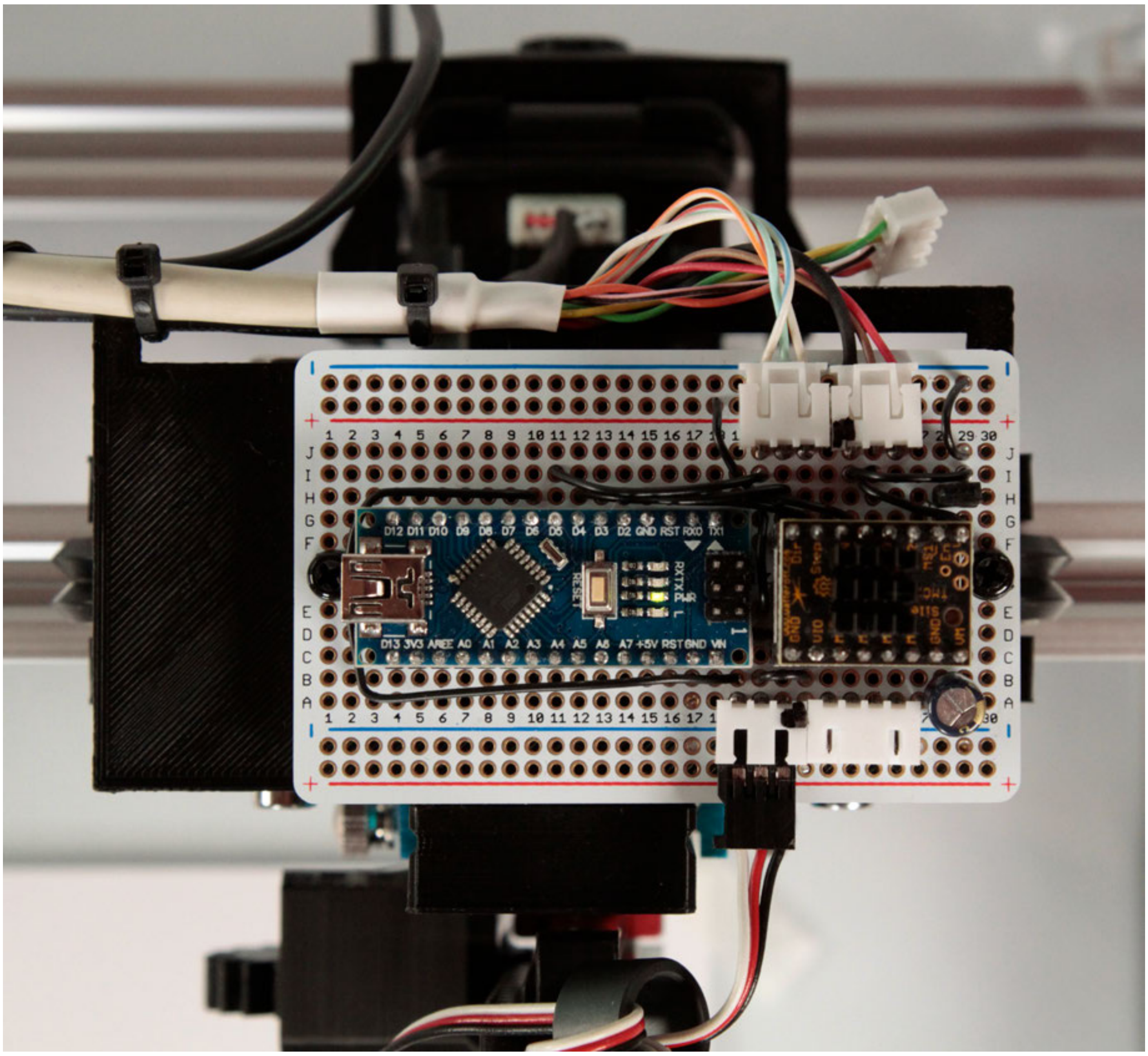
Detail photographs in high resolution



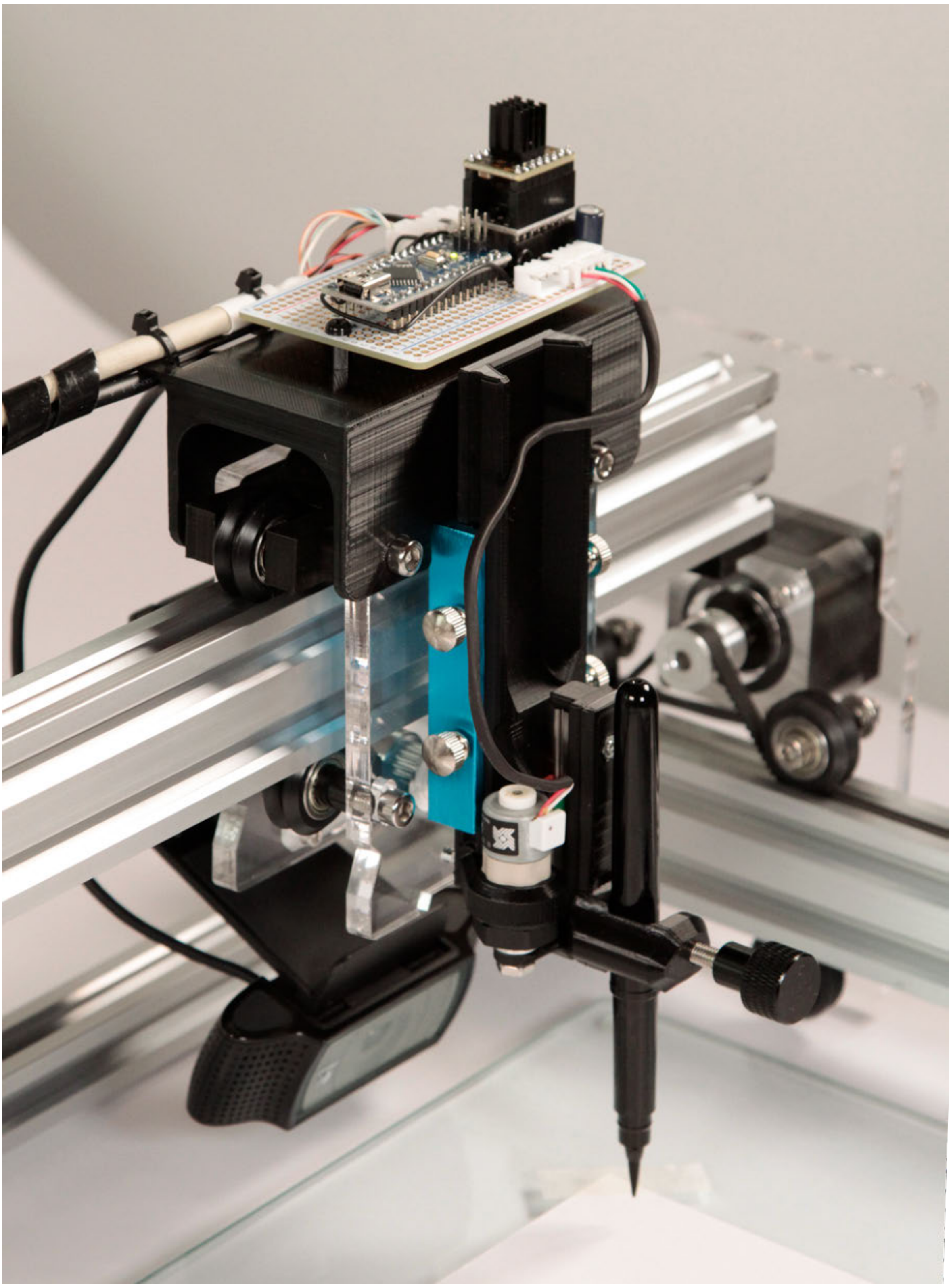
The resulting experimental pen plotter, photograph, Brenda Jiménez and Martin Bircher, 2022.



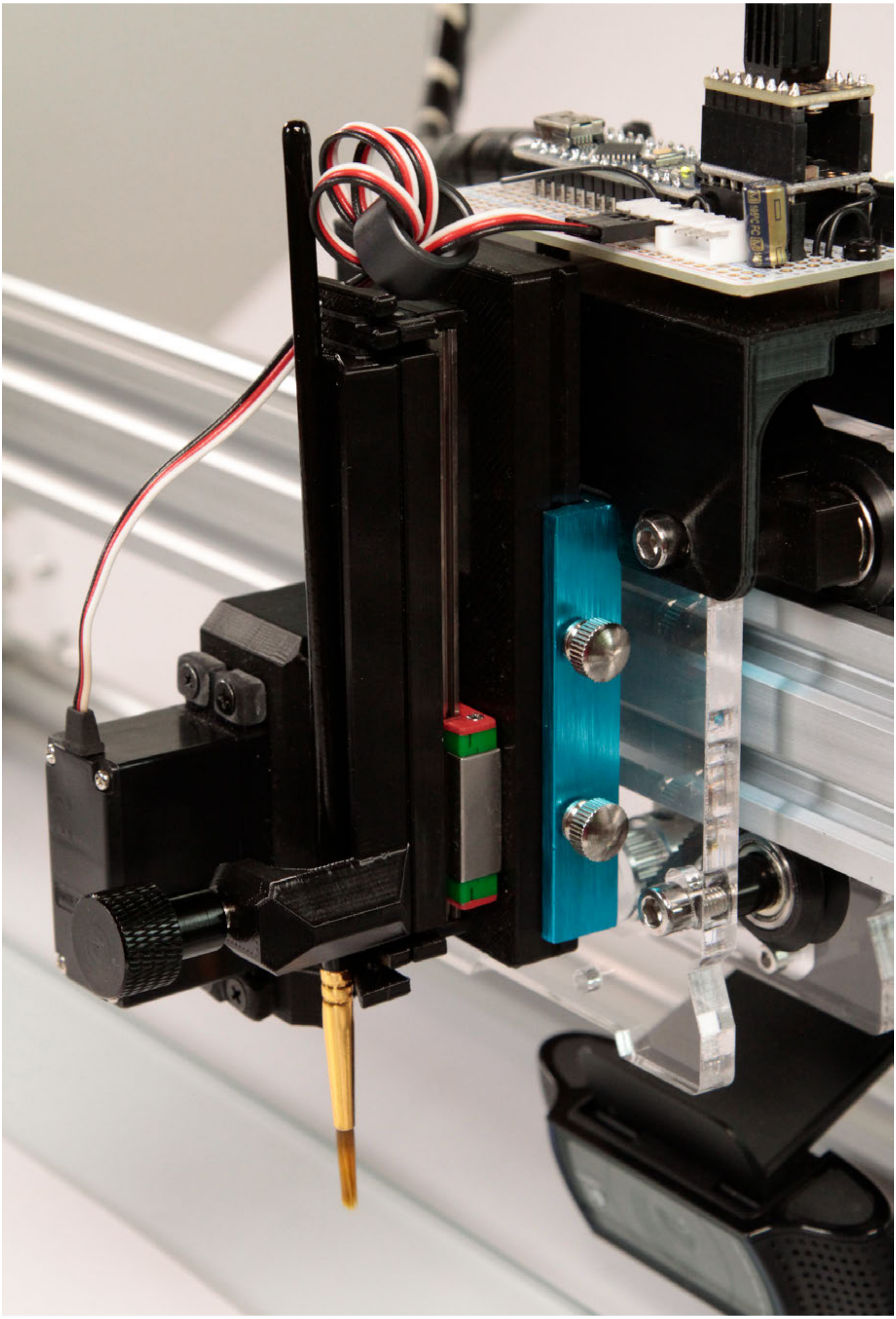
The custom mount for the main control board, photograph, Brenda Jiménez and Martin Bircher, 2022.



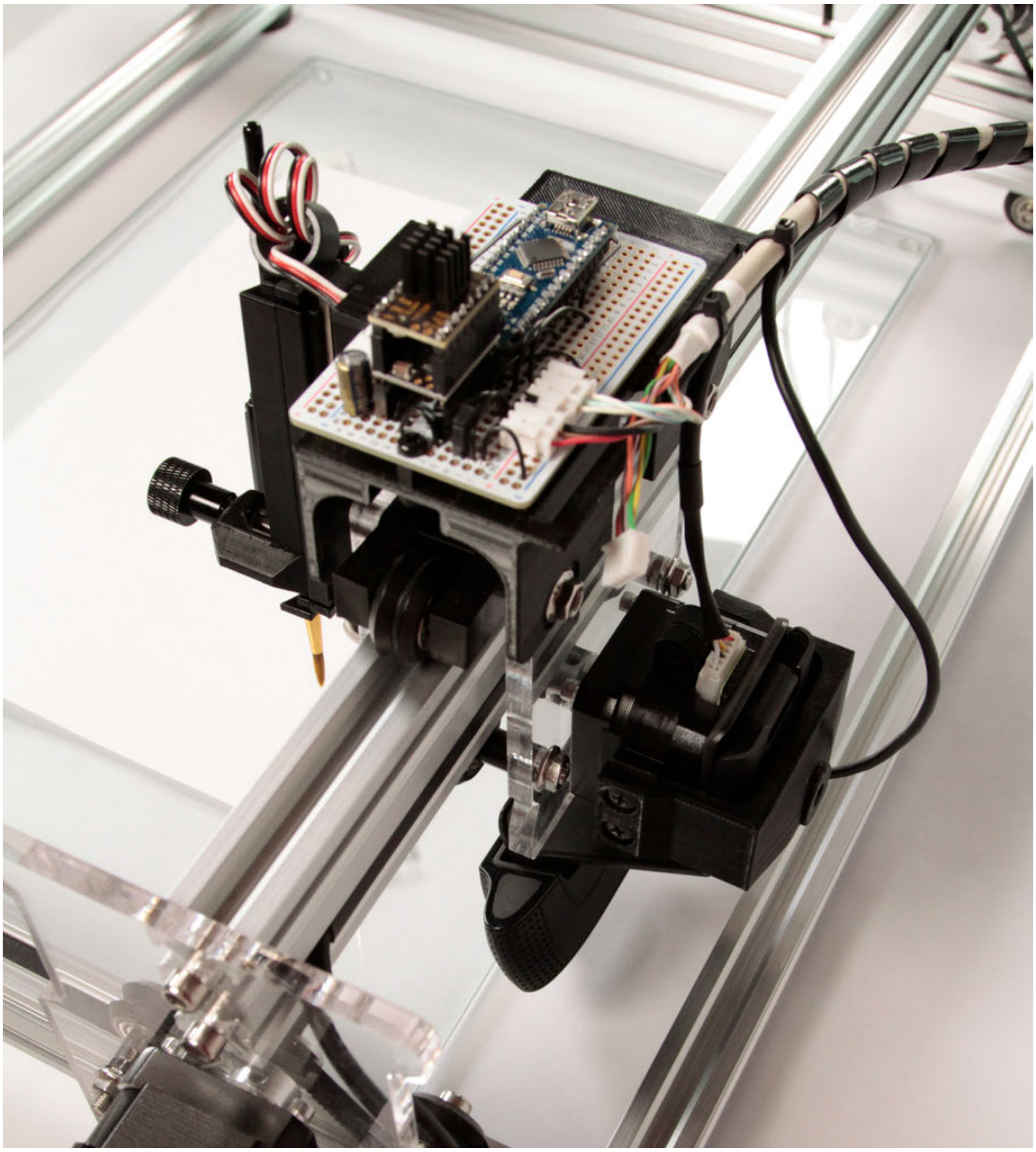
The custom sub-control board for the pen-lift mechanisms, photograph, Brenda Jiménez and Martin Bircher, 2022.



The high-precision short-stroke pen-lift mechanism, photograph, Brenda Jiménez and Martin Bircher, 2022.



The low-precision long-stroke pen-lift mechanism, photograph, Brenda Jiménez and Martin Bircher, 2022.



The pen carriage with the pen-lift mechanism, control board and camera holder, photograph, Brenda Jiménez and Martin Bircher, 2022.