Synaesthetic Strokes

A Biology-inspired, adaptive and collaborative robotic system for painting

Impression of the room installation *Synaesthetic Strokes* (2023) at the Collegium Helveticum, part of the exhibition Data Alchemy — Observing Patterns from Galileo to Artificial Intelligence, curated by Adrian Notz and Liat Grayver. Photo by Marcus Nebe, © VG Bild Kunst / Liat Grayver.

In 1967, Marshall McLuhan proposed that "All media are extensions of some human faculty — psychic or physical"[1] and, further, that "electric circuitry [is] an extension of the central nervous system."[2] This would suggest that all forms of media act as extensions of our faculties, thereby shaping our various modes of existence. This perspective prompts us to reflect on how the mediums we utilize to navigate the world influence the intellectual intuition we employ. As technological advancements continue to reshape our being, it becomes increasingly necessary that we critically examine the role of media and its implications for our understanding and engagement with the world. As artists, we bear a responsibility to engage with the emerging phenomena brought about by computer science and engineering. The broader field of arts, particularly within those areas with a focus on craft-based practices, is currently witnessing an unprecedented set of challenges and opportunities presented by machine learning technologies. We should reflect on but also ourselves investigate these emerging creation and fabrication methodologies in order to be able to collaborate and work alongside different degrees of machine agencies, as they come to play in the various forms of what is today referred to as "artificial intelligence" (AI).

Embracing robotic systems operated by AI in the artistic process by no means implies an irreverent disregard for the physical knowledge that underlies craft-based practices. On the contrary, it presents an opportunity to transcend the limitations of the purely digital medium of image production and delve into new realms of artistic exploration. By incorporating artistic concepts as subjects of investigation and potential re-evaluation in the context of AI, we can push the boundaries of our understanding and challenge traditional notions of creativity. By creating an interactive and adaptive platform (co-painting with a machine) and working with implicitly complex materials and tools (paint and brushes), I wish to challenge the absolutism of screen-based, computer-generated image production, adding a level of complexity — inherent to the use of organic materials — and surprise into the outcome of the work, freeing it from acquiesced understandings of painting and image making. Through further development of an interactive

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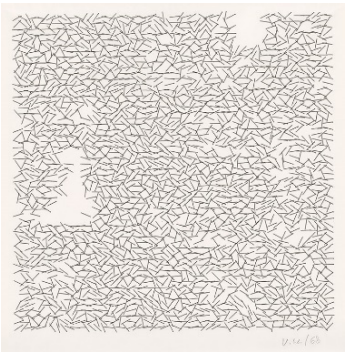
1 Marshall McLuhan and Quentin Fiore, *The Medium Is the Massage: An Inventory of Effects*, 1967, p. 26. Follow-up to McLuhan's 1964 publication of *Understanding Media: The Extensions of Man*, in which his famous phrase "the medium is the message" first appeared.

2 Ibid, 40.

human-machine platform of robotic painting, my artistic work challenges conventional approaches to the generation of visual information using learning machines, as they predominantly serve to increase, expand and recreate stochastic forms of existing cultural-æsthetic tendencies and artefacts.

During a 10-month Junior Fellowship (September 2022 – June 2023) at the Collegium Helvetica at the ETH Zurich, I developed the artwork *Synaesthetic Strokes*, in which I sought to shed new light on the ever-growing relationship between human expressivity and mechanical operations. The technical development was done by Lioba Schürmann under the supervision of Prof. Dr. Giacomo Indiveri from the Institute of Neuroinformatics at the University of Zurich (UZH) and the ETH Zurich. Additionally, valuable guidance was given by Dr. Giulia D'Angelo and Prof. Dr. Chiara Bartolozzi from the Italian Institute of Technology. This exploration aimed to investigate the dynamic interplay between humanity and its media, forging a deeper understanding of the intricate connection between human expressiveness, creativity and technological innovation — from the traditional practices of manual craftsmanship to autonomous machine operation.

A core feature of 20th-century computer-based visual art is the use of algorithmic procedures to produce geometrical forms and patterns that merge deterministic operations, random / infinite concepts and forms. For example, the output (style as well as form) of such computer artists as Vera Molnár[3] (from 1968 onwards) and Harold Cohen[4] (AARON, 1973) was limited by the algorithmic code used to derive geometric shapes and patterns, or line drawings, respectively. Recent research interest in robotic painting, exemplified by projects such as e-David[5], FRIDA[6] and "Paul" (a drawing robot by the artist Patrick Tresset[7]) has employed advanced computer vision and graphics to enable closed-loop visual feedback system.



Left: Vera Molnár (b. 1924), *Interruptions*, 1968. Black ink on a translucent paper, created on a Benson platter, 12-5/8" x 12-5/8" (32 x 32 cm). Gift of Agnes Gund, 2017.353. © Vera Molnár / Artists Rights Society (ARS), New York.

Centre: Harold Cohen, *T04167 Untitled Computer Drawing*, 1982. Black ink and textile dyes on machine made, wove paper, 575 x 765 cm (22-3/4 x 30"). Watermark BFK Rives / France. The black ink outlines of the abstract shapes were drawn automatically by a computer, programmed by the artist. *Tate Gallery: Illustrated Catalogue of Acquisitions 1986–88*, London: Tate Publishing, 1996.

Right: Painting of Frida Kahlo by the painting robot Frida. Source: http://pschaldenbrand.github.io/frida

However, from the perspective of craftsmanship, the utilization of machine-based operations poses a significant artistic constraint. These operations are often governed by a predefined "default state" that aims to optimize the

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[3] Computer art pioneer from Hungary, based in France since the 1960s. See: Aline Guillermet, "Vera Molnar's Computer Paintings," *Representations* 149 (2020), p. 1–30.

[4] Artist and engineer who was based in London. See: Louise Sundararajan, "Harold Cohen and AARON: Collaborations in the Last Six Years (2010–2016) of a Creative Life," *Leonardo* 54/4 (August 2021), pp. 412–417. http://doi.org/10.1162/leon_a_01906 Also see: Paul Cohen, "Harold Cohen and AARON," AI Magazine 37/4 (Winter 2016), pp. 63–66. http://doi.org/10.1609/aimag.v37i4.2695

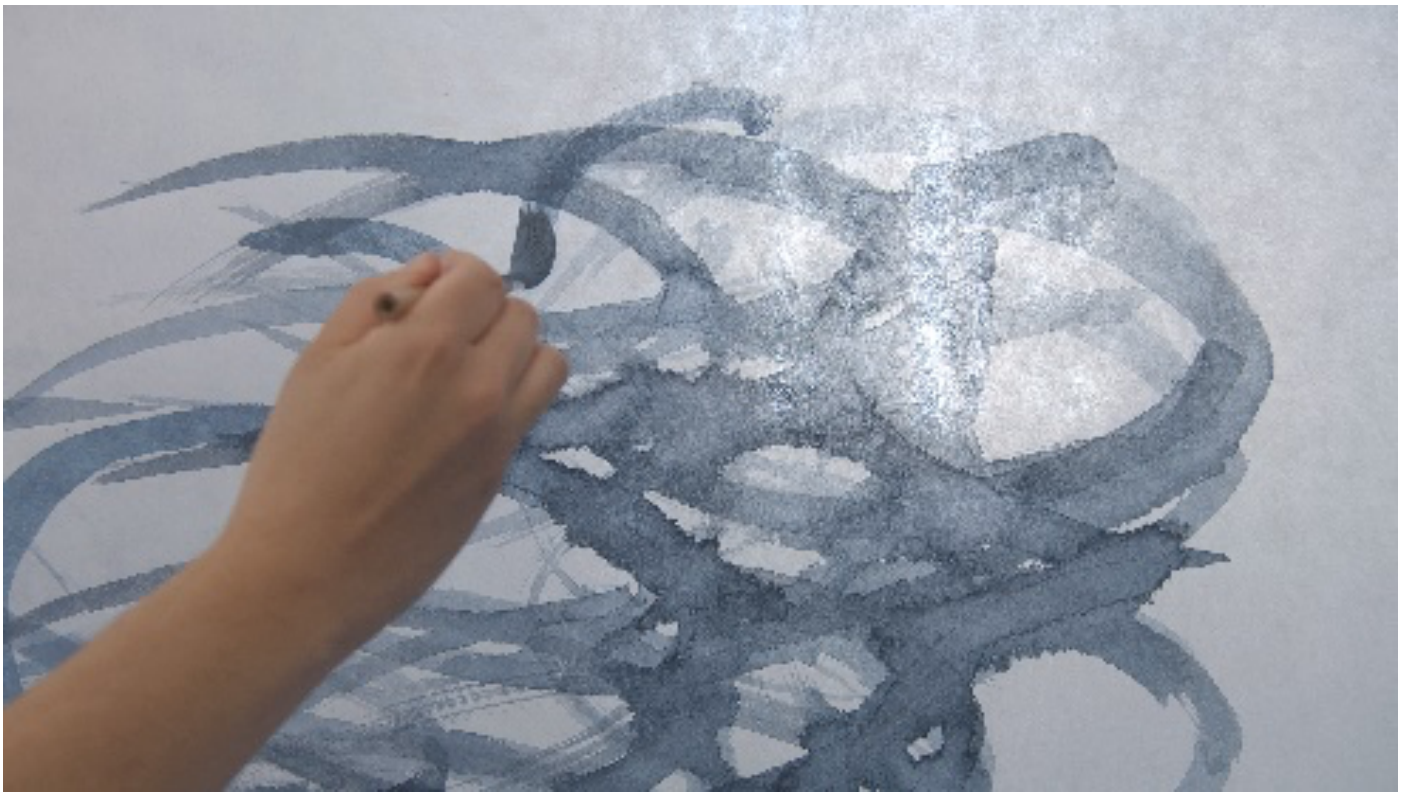
[5] Thomas Lindemeier, "e-David: Non-photorealistic rendering using a robot and visual feedback," unpublished doctoral dissertation, University of Konstanz, 2018.

[6] Peter Schaldenbrand, James McCann and Jean Oh, "FRIDA: A Collaborative robot painter with a differentiable, real2sim2real planning environment," Cornell University, arXiv:2210.00664, 2022. http://doi.org/10.48550/arXiv.2210.00664

[7] Similar to Harold Cohen, Tresset's work bridges the realms of artistic creation and scientific publications. My initial encounter with "Paul" was in 2012 during a visit to London. At that time, Tresset presented his first version of the drawing machine in a small gallery space he had rented. Over the years, Paul the robot has undergone significant evolution, embracing diverse machine learning approaches to enhance its creative process. http://patricktresset.com

work and its outcomes. However, this approach is largely incompatible with certain aspects of process-based explorations that are inherent in painterly practices, such as the ability to respond and adapt to the behaviour of materials such as paint and brushes. Rather than exerting complete control over these materials, craftsmen often seek to engage in a dialogue with them, allowing their characteristics and behaviour to *influence* the artistic process. This emphasis on responsiveness and interaction with materials is at odds with the rigid optimization frameworks of machine-based operations.

Building upon Ursula Franklin's definition of holistic and prescriptive technologies[8], within the artistic practice of creating and conceptualizing the installation and performative artwork *Synaesthetic Strokes* I was particularly interested in working adaptively to an ever-changing world of æsthetic exploration, with the tasks and outcome co-existing more as an open-end relational process than a set of fixed rules. In contrast, thus far, my robotic painting work was dependent on custom-developed computer programs, which have constrained some of the æsthetic avenues I wished to explore, as the limitations were defined by specific code architectures. The utilization of neuromorphic sensory-processing technology, a biology-inspired manner of implementing cognitive agents, presented an intriguing opportunity to delve into the realm of interactive robotics. This technology offered a real-time, dynamic interactive system that deviated from fixed algorithmic procedures and limited datasets, providing a more adaptive approach for exploring the art of brushstrokes in the context of robotics-assisted painting.



***Synaesthetic Strokes* (2023). Photo by Marcus Nebe, © VG Bild Kunst / Liat Grayver.**

In the creation of the work *Synaesthetic Strokes*, I developed novel methodologies for creating an active perception system that facilitates creative generative processes. This is achieved through the integration of a dynamic vision sensor for visual feedback and a neuromorphic chip for sensory processing and pattern recognition, seamlessly connected to a robotic arm with a force sensor, operating in real time. The focus of this exploration lies in the attempt to comprehend and replicate the essence of a single brushstroke.

In my pursuit of an intrinsically collaborative and interactive working process between humans and machines, I aim to achieve a profound level of synergy. In this vision, the machine not only responds to the visual state of the painting but also delves into the tactile realm of materials, extracting information from the brush and paper themselves. It then adapts its physical implementation of the following stroke accordingly. In my previous artistic research done in the field of robotics-assisted painting with the e-David painting robots research team at the

[8] Ursula M. Franklin, "The Real World of Technology", CBC Massey Lecture Series, Canadian Broadcasting Corporation, 1990.

University of Konstanz, in art projects such *Incomputable Imagery: Reimagining the Brushstroke*[9] (using a brushstroke creation software developed by Dr. Daniel Berio in 2021[10]) and "Brushstrokes in the Digital Age"[11] (from 2016–18, using software developed by Dr. Thomas Lindemeir[12] and with the support of Marvin Gülzow[13]), I solely relied on methods of computer graphics and computer vision to process static images of a stroke, aiming to translate them into dynamic action.

The approach taken in *Incomputable Imagery: Reimagining the Brushstroke* aimed to define the essence of a brushstroke and explore our perceptual abilities to replicate it.[14] It utilized algorithmic systems that generate brushstroke vectors, leveraging data extracted from the visual feedback mechanism. The iterative procedure starts with an initial "seed" stroke made by the artist. A snapshot of this stroke is taken by the camera and analyzed by a program written by the e-David team and Berio. A centreline and a width profile are then inferred from the image of the stroke using a simplified version of the method described in [Berio et al. 2022]. Using this data, a new stroke is constructed that traces the outlines, centre line and gradient of the input. At each step in this reiterative process, a different vision algorithm is used to reconstruct a new image of the stroke and the e-David executes a new stroke that differs from the original due to the imperfections of the reconstruction procedure and the differing visual data extracted from each subsequent stroke in the process.

At regular intervals, the robot dips the brush into one of a number of ink containers, each containing ink diluted with a different amount of water. This procedure results in an ever-changing sequence of strokes that ultimately depend on a combination of variations in the amount and dilution of ink used by the robot and the reconstruction accuracy of the vision algorithm used at a given step.

[9] Exhibited at the Kulturzentrum am Münster, Konstanz (Germany), 5 November – 5 December 2021.

[10] See: Daniel Berio, Frederic Fol Leymarie, Paul Asente and Jose Echevarria, "StrokeStyles: Stroke-based segmentation and stylization of fonts," *ACM Transactions on Graphics* 41/3 (June 2022), pp. 1–21. http://doi.org/10.1145/3505246

[11] This series of works was created in collaboration with Thomas Lindemeier, who developed a custom-made program utilizing algorithmic processes to define the location of strokes as compositional elements. The inspiration for this project was drawn from texts like "Entropy and Art: An essay on disorder and order" by Rudolf Arnheim (1971). Information about this project can be consulted on the artist's website: http://www.liatgrayver.com/projects/Brushstrokes-in-the-Digital-Age

[12] Thomas Lindemeier, Marc Spicker and Oliver Deussen (2016), "Artistic Composition for Painterly Rendering," *VMV16: Vision, Modeling & Visualization* (Geneva: The Eurographics Association, 2016). http://doi.org/10.2312/vmv.20161350

[13] Jörg Marvin Gülzow, Liat Grayver and Oliver Deussen, "Self-Improving Robotic Brushstroke Replication," *MDPI* Special Issue "The Machine as Artist (for the 21st Century)" (2018). http://doi.org/10.3390/arts7040084

[14] More information is available at: http://www.liatgrayver.com/projects/InComputable-Imagery-Reimagining-the-brushstroke

Impression from the show *Incomputable Imagery: Reimagining the Brushstrokes* (2021). On the right is the visual feedback pipeline, generating the stroke's path based on the visual output of the previous stroke. Due to limitations in computer vision, overlapping strokes were not detectable.

***Just Before it Snaps*. Liat Grayver and the e-David. Acrylic on board, 40 x 50 cm, from the series "Brushstrokes in the Digital Age" (2017).**

In *Incomputable Imagery: Reimagining the Brushstrokes*, the styles and techniques of operating the brush were predetermined, significantly restricting the genuine sense of collaboration between human and machine within the system. As the only data that could be extracted to inform the system about the state of the stroke was *visual*, it was essentially impossible to plan a subsequent stroke that would *intentionally* overlap prior strokes. In existing computer vision techniques, intersecting marks are perceived by the system as a single, unified image. No information regarding the state of the paper, deformation of the brush or brushstroke velocity was available in the process. Gestural actions could not be designed, as the stroke was treated as static information, as an image. The system was essentially limited to merely planning the vectors of the next stroke to be executed.

Revisiting the task of recreating a brushstroke using artificial systems that incorporate DVS cameras, force sensors and neuromorphic processors has granted direct access to real-time data. This significant development makes it possible to create and work with a new range of dynamic operations, which are at the core of the new work, *Synaesthetic Strokes*. This newfound capability has not only enhanced the machine's "understanding" of the intricate aspects required to recreate a stroke but has also allowed me to assess the stroke's unfolding state, fostering a deeper level of physical collaboration akin to classical craftsmanship, where the affordances, impacts and potentialities of the human, medium and machine components comprising the system are intimately intertwined.

Technical Setup

The creation of *Synaesthetic Strokes* was only possible following the establishment of a new and innovative robotic painting studio during my fellowship at the Collegium Helveticum, combining meticulous planning and coordination of the engineering and artistic concepts. Support from several institutions at ETH Zurich and UZH played a crucial role in the process. The technical setup involved a UR10 Robot, on loan from the Institut für Technologie in der Architektur and Gramazio Kohler Research Group at the ETH Zurich. The robot was equipped with a SensONE 6-axis force torque sensor, provided by Bota Systems, boasting a serial interface for seamless integration. A tripod was

utilized to position a web camera and a Dynamic Vision Sensor (DVS) camera[15] positioned in front of the painting area. The Neuromorphic DYNAP-SE1 Processor, created at the Institute of Neuroinformatics (UZH), was crucial in analyzing the brushstrokes using data captured by the DVS.[16] The processor consists of mixed-signal silicon neuron circuits designed for emulating spiking neural networks, and was used to generate motor commands that made it possible to recreate similar but not identical brushstrokes, matching their timing and dynamics.

The robotic painting setup included a custom-built paper holder, produced by the workshop of the UZH's Physics Institute, that was connected to an aluminum frame with a magnet-based fixation mechanism. This allowed for continuous painting, affording the human operator control to reposition the roll so that the robot has a blank (clean) section to paint on as needed.

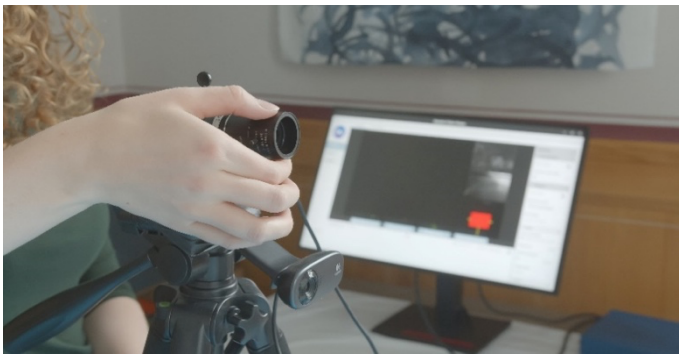
Additionally, the setup involved a lighting studio system from the Zürcher Hochschule der Künste (ZHdK) that ensured a stable environment for visual data collection. A 3D-printed brush holder, designed by Zurich-based Design Engineer Carl P-Conquilla, held two different sizes of calligraphic brushes, which make it possible for the system to produce an extraordinarily wide range of brushstroke characteristics. The setup also featured a Plexiglas palette with six glass containers, holding sumi ink or blue ink, white ink, and two containers of water for each of them for dilution or to create colour gradients. To explore different surface resistances and transparency effects, Chinese Xuan rice paper and Mulberry paper were employed.

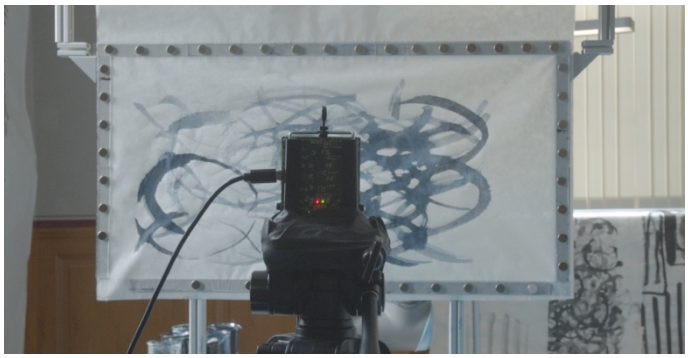
Impression of the room installation *Synaesthetic Strokes* (2023) at the Collegium Helveticum, part of the exhibition Data Alchemy — Observing Patterns from Galileo to Artificial Intelligence, curated by Adrian Notz and Liat Grayver. Photo by Marcus Nebe, © VG Bild Kunst / Liat Grayver.

The various collaborators, partners and technologies involved in *Synaesthetic Strokes* made it possible to build on and extend the artistic research begun in the context of *Incomputable Imagery*. The implementation of bio-inspired hardware and software has already afforded impressive results exploiting the potential of human-robot collaboration in the realm of painting, and future projects will have access to immensely valuable resources as a direct outcome of this collaborative artistic and scientific project

[15] DVS is a silicon retina inspired by transient cells in mammalian retinas.

[16] See, for example, Patrick Lichtsteiner, "A 128 × 128, 120 dB, 15 µs Latency Asynchronous Temporal Contrast Vision Sensor," *IEEE Journal of Solid-State Circuits* 43/2 (February 2008), pp. 566–576. http://ieeexplore.ieee.org/document/4444573



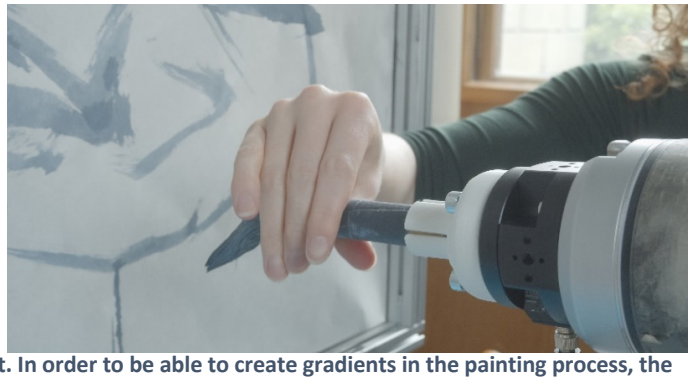


Left: Visual information about the brushstroke's trajectory and velocity is captured by a Dynamic Vision Sensor (DVS) camera. It encodes changes of light intensity with ultra-low latency. Photo by Marcus Nebe, © VG Bild Kunst / Liat Grayver.

Right: Frame and paper holder. A custom-made magnetic frame fixates a transparent sheet of paper between the robot and the DVS camera. Photo by Marcus Nebe, © VG Bild Kunst / Liat Grayver.

Left: Impression of the working setup. Photo by Marcus Nebe, © VG Bild Kunst / Liat Grayver.

Right: Neuromorphic processor. The Dynap SE-1 neuromorphic processor developed by Prof. Giacomo Indiveri at the Institute of Neuroinformatics (UZH/ETH) emulates spiking neural networks that are used for sensory processing and motor control of the robotic arm. Photo by Marcus Nebe, © VG Bild Kunst / Liat Grayver.



Left: Six glass containers are installed as a palette for the painting robot. In order to be able to create gradients in the painting process, the containers are positioned in the following order: blue or black ink, water, water, white ink, water, water. Photo by Marcus Nebe, © VG Bild Kunst / Liat Grayver.

Right: Sensor and brush holder. Pressure feedback from Bota Systems' SensONE force-torque sensor is incorporated in the painting process. A custom 3D-printed brush holder attaches the calligraphic brush to the robot's flange. Photo by Marcus Nebe, © VG Bild Kunst / Liat Grayver.

Artistic Process

It is my *physical knowledge*, the embodied artistic experience I have gained from over 20 years of professional involvement in various forms of painting and traditional printmaking, that has led me to focus on the exploration of the brushstrokes as a key element in the development of our global and local cultural and perceptual æsthetic history. The brushstroke, in all its diverse forms, serves as a singular tool of communication encountered in paintings and drawings across different epochs. At the heart of this artistic practice is a profound exploration of the act of creating a painting itself, emphasizing the process of crafting a line rather than the final artwork.

Close-up of overlapping strokes from the work *Synaesthetic Strokes* (2023) displaying the diffusion of ink in wet-on-wet and wet-on-dry situations, creating layers of paint. Photo by Marcus Nebe, © VG Bild Kunst / Liat Grayver.

Synaesthetic Strokes utilizes artificial learning systems that are inspired by the structure and functionality of biological neural networks to explore how the body and mind perceive not only the visual elements of the painting (the image), but also the intricate processes by which it was brought into existence — capturing both the form perceived by the eye and the energy felt within. The entire pipeline is bioinspired, not only the cameras, and everything along the process is designed to emulate neurons, with both excitatory and inhibitory currents implemented in the system.

Throughout the process of artistic exploration, passive materials respond to the active manipulation imposed upon them. Both the passive and active elements play equally significant roles in the creative process and the final outcome. Each aspect along the way must be meticulously assessed in order to faithfully recreate a brushstroke. Factors such as brush deformation, ink state, overlapping strokes, velocity, tilt, vectors and pressure all contribute to the physical properties that are etched into the visual manifestation of the stroke itself. Inspired by the principles of Japanese calligraphy, this work seeks to strike a delicate balance between controlling the materials and embracing bodily movements, adapting to the idiosyncrasies of the paper and ink as they inform the calculation of the subsequent stroke.

The system pipeline begins with a human creating a brushstroke using a calligraphic brush, ink and a large roll of mulberry paper measuring 1 x 60 m. The machine then attempts to reproduce the stroke by analyzing data captured from a Dynamic Vision Sensor (DVS) camera, initially focusing on the stroke's direction and velocity. As the process unfolds, the machine incorporates additional data from the force sensor and robotic arm to generate its own stroke.

To enable a continuous painting experience and showcase the evolutionary state of the stroke, I have implemented a specially designed paper holder and magnetic frame. This dynamic setup allows growth of the painting and provides the human operator with the ability to subjectively determine when the paper is sufficiently saturated or æsthetically pleasing. At this point I pause the painting process, scroll down to a clean section of the paper and allow

the machine to continue generating new strokes. This interactive setup empowers the artist to actively engage with the machine in shaping the artistic output, highlighting the collaborative nature of the artwork. It combines the precision and capabilities of the machine with the subjective decisions and artistic sensibilities of the human operator, resulting in a unique and evolving artistic creation. The technical components of this process were overseen and largely managed by Lioba Schürmann.

Upon painting approximately 5–7 metres of paper, the painting was cut from the long scroll and suspended from the ceiling to the floor of the historical building at the ETH Observatory, where the exhibition was held. This arrangement gradually filled the entire room with a combination of mechanical and human-made strokes, immersing visitors in a sea of brushstrokes and challenging them to discern between those created by the machine and those by a human. The overlapping of strokes, whether wet on dry or wet on wet, results in the formation of intricate and complex compositions, 1 m wide and up to 7 metres in length. This composition emerges from a fusion of algorithmic procedures, the intricate behaviours inherent in the materials and the machine's perceptive understanding of the previous stroke. The outcome is an organic evolution of strokes, embodying the dynamic interplay between human creativity and decision-making in conjunction with machine processes.

The resulting performative artwork embodies a dynamic and collaborative exploration between humans and artificial systems, deconstructing the essence of a brushstroke and provoking enquiries into its nature. It prompts reflection on the perception and replication of brushstrokes by artificial entities, as well as the profound significance of the technical complexities inherent in this seemingly simple task. These challenges bear relevance not only in the context of rapid advancements in autonomous machines but also in understanding the capabilities and boundaries of human agency.

The primary artistic objective of this project was to develop an adaptive artificial behaviour system that incorporates principles of traditional craftsmanship to create robotic-based paintings. These paintings serve as a foundation for training the machine to achieve complex and nuanced outcomes and reactions throughout the painterly process. The long-term goal of this project is the creation of a brushstroke depository, or library, of "gestural" robotic movements (tactile-physical) and presets of rules and "conditions" for their execution (perceptual-cultural), an accessible platform that will be built later for broader use in robotic painting (both hardware and software). As the library will compartmentalize not only individual brushstrokes as gestures, but also visual information, it will be possible to integrate the repository into the visual feedback mechanism of another robotic painting interface. As an example of the many important implications this holds for the future of robotic painting, this will afford users with the possibility to decide on the level of human control or autonomous robotic painting creation, as it will be possible to set rules for the use of individually defined variants of stroke characteristics. This exploration aimed to redefine the traditional art form of painting in the context of our technology-driven era, while examining the influence of robots as interactive painterly tools on creativity, authorship and agency in artificial systems.

Close-up of overlapping strokes from the work *Synaesthetic Strokes* (2023) displaying the diffusion of ink in wet-on-wet and wet-on-dry situations, creating layers of paint. Photo by Marcus Nebe, © VG Bild Kunst / Liat Grayver.