Fluid Brush

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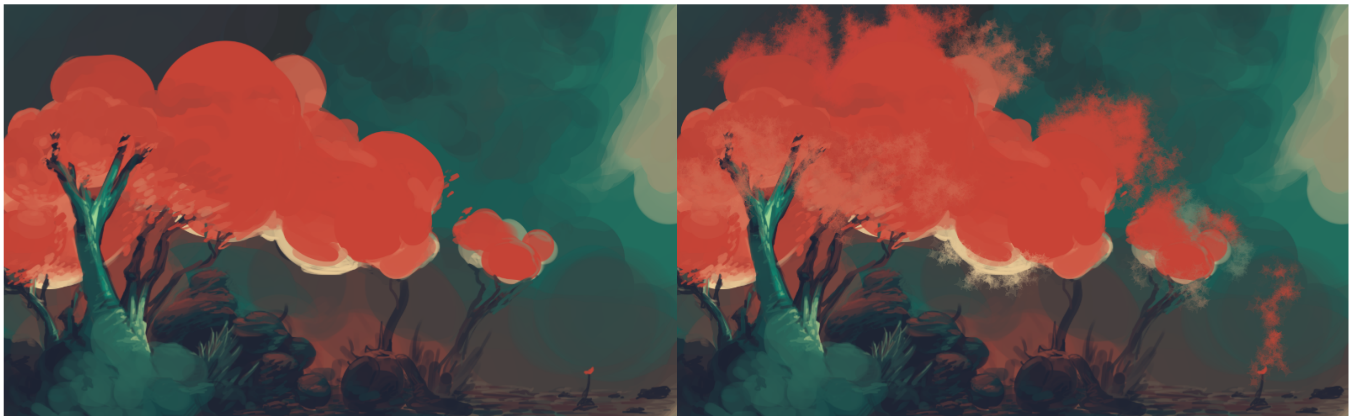

Figure 1: The Fluid Brush medium provides artists with easy access to animated fluid motion using the existing metaphors of traditional brush controls. This facilitates effects such as the small scale turbulent motion shown in this fiery tree © Evan Kight, as well as directional motion based on stroke, without the need for a highly technical, digital interface.

ABSTRACT

Digital media allows artists to create a wealth of visually-interesting effects that are impossible in traditional media. This includes temporal effects, such as cinemagraph animations, and expressive fluid effects. Yet these flexible and novel media often require highly technical expertise, which is outside a traditional artist's skill with paintbrush or pen. Fluid Brush acts a form of novel, digital media, which retains the brush-based interactions of traditional media, while expressing the movement of turbulent and laminar flow. As a digital media controlled through a non-technical interface, Fluid Brush allows for a novel form of painting that makes fluid effects accessible to novice users and traditional artists. To provide an informal demonstration of the medium's effects, applications, and accessibility, we asked designers, traditional artists, and digital artists to experiment with Fluid Brush. They produced a variety of works reflective of their artistic interests and backgrounds.

CCS CONCEPTS

• **Computer Graphics** → *Non-Photorealistic Rendering*; *Graphics input devices*;

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non-photorealistic rendering; paint systems; sketching; animation

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1 INTRODUCTION

Art is an ever-evolving form that includes traditional media, like ink and watercolor, and new media, which is an ongoing experiment with material and process for creating novel, often hybrid, forms of art [Tribe et al. 2009]. Digital forms of media have the ability to convey temporality through animation — a powerful feature difficult to achieve in traditional forms of art such as painting and drawing. Fluid motion is of particular interest due to its highly distinct, physically-based nature, but controlling and animating fluids is tedious and challenging.

The tools of animators and modelers are intricate programs based on Computer-Aided Design (CAD), whereas traditional painters rely on a simple set of equipment, such as paintbrushes, to create a large array of effects. We propose *combining the intuition of brush-based interfaces*, found in painting and calligraphy, with *fluid animation* available through digital tools in order to bring *new media effects to artists of all backgrounds.*

Our main contribution is accessible fluid effects for traditional and novice artists, and Fluid Brush accomplishes this by retaining the brush-based metaphors of painting, while incorporating animated fluid motions. Artists use a stylus and tablet interface to mimic the interactions of a paintbrush, while the system provides underlying functionality for expressing fluid flow. Effects include a stippling technique to create a soft spread turbulent effect demonstrated in Figure 1, and the calligraphic variation of stroke quality, with its strong, laminar directionality, shown in Figure 2.

1.1 Artist Evaluation

As an informal study into potential effects and applications of our system, we asked 15 artists, including designers, traditional artists and technical artists, to experiment with Fluid Brush. They established their own effects and techniques, several of which are reminiscent to effects in traditional media. Unlike complex digital interfaces, Fluid Brush's minimal GUI and simple stylus controls allowed traditional artists to generate such effects within minutes. Artist results are included in the supplemental material, which display two periods of looping animation to demonstrate the range of visual effects possible with Fluid Brush, as well as in the short video.

2 PREVIOUS WORK

Figure 2: Fluid Brush can emulate calligraphic strokes with strong directionality while incorporating animated, turbulent fluid flow.

Digital forms of traditional media have ranged from charcoal [Bleser et al. 1988] to oils and acrylics [Baxter et al. 2004]. Computational fluid dynamics (CFD) has been explored in the graphics community [Bridson and Müller-Fischer 2007] for creating fluid animations, and is used in Curtis et al.'s watercolor technique [Curtis et al. 1997] and the sumi-e system, MoXi [Chu and Tai 2005], as well as the painting programs that extend them [Blaškovič 2016; Chu 2017]. In all of these systems, diffusion and advection simulate the flow of paint from brush to canvas to recreate their respective traditional medium rather than express a new type of digital media.

Novel, digital effects that use stylus controls include Kalnins et al.'s WYSIWYG system for non-photorealistic rendering effects [Kalnins et al. 2002], the Draco system [Kazi et al. 2014], and Hierarchical Motion Brushes [Milliez et al. 2014]. Draco and Hierarchical Motion Brushes use a stylus interface to provide directional control of art assets, but these systems work with sprite assets and textures rather than fluid motion. The WYSIWYG system is designed for painting, and therefore does not focus on animation.

Constraining fluid motion is a well-studied area in the graphics community. Techniques can provide high-level controls [Shi and Yu 2005; Treuille et al. 2003], where the user specifies key-frame targets, mid-level controls [Barnat et al. 2011], where the user has a general notion of a target, or low level controls [Madill and Mould 2013], where the user controls physics-based parameters to manipulate the fluid. While these systems create a wide range of effects, they often require expert users, who have experience with digital art GUIs and some understanding of fluid flow. Similarly, Nowrouzezahrai et al. applied these concepts to controlling lighting in a brush-like manner, but the system is designed for expert digital artists with a technical understanding of lighting [Nowrouzezahrai et al. 2011].

Since Fluid Brush is designed to be accessible to artists of all backgrounds and skill level (including traditional and hobbyist artists), we captured the feel of traditional painting by emphasizing "brush-style" controls. Similar ideas include Nasri et al.'s sketch-based technique for designing subdivision models [Nasri et al. 2009] and Kim et al.'s controls using 3D NURBS curves [Kim et al. 2006], but both techniques focus on 3D modeling. Other work in the area of brush controls includes haptic brushes like DAB by Baxter et al. [Baxter et al. 2001], and work by Yeh et al. [Yeh et al. 2002]. Both of these systems use a haptic brush which allows accurate digital modeling of painting techniques, but the additional hardware requirement raises the barrier to entry for traditional and hobbyist artists. To make Fluid Brush as accessible as possible, our system relies solely on a basic stylus-and-tablet interface to remain low-cost and easy-to-learn.

The Smoke Brush system [Abraham and Fussell 2014] also constrains smoke to a brush stroke, but it only uses turbulent motion. Smoke Brush therefore provides little control over the smoke particles beyond brush radius and turbulent velocity, and it lacks models for laminar flow and brush controls. Without these features, artists cannot incorporate stroke cohesion or directionality into brush effects, which limits the possibilities of the medium. Fluid Brush incorporates pressure, tilt, and brush speed to create variation and artistic intent within a line, and the effects artists achieved using these controls are discussed in the "User Reaction" section.

3 DESIGN STUDY: TRADITIONAL BRUSH CONTROLS

Fluid Brush's interface draws inspiration from watercolor and sumi-e ink painting, because their water-based effects have much overlap with Fluid Brush's animated fluid motions. Even as Fluid Brush effects expand on digital media, the controls and techniques of traditional media guide interactions within our system.

Watercolor has a range of effects, many based on brush and canvas saturation. Some of the standard techniques are discussed by Whyte [Whyte 1997], including *flat wash on wet paper* for a translucent airiness, *flat wash on dry paper* for controlled edges and greater opacity, and the *graduated wash* for a lighter gradient effect. It is also possible to create a *variegated wash* involving two colors that blend together.

The *wet-into-wet* technique is one of the most distinctive and recognizable effects in watercolor, where fresh pigment is applied to a still-wet area of the canvas. Although an experienced artist can anticipate and control a great deal of this process, there is an inherent spontaneity to it, since the exact nature of the blending depends on the brush stroke, volume of water and paper texture.

By applying a second color over an initial, dried pigment color, *glazing* creates the appearance of a third color, which adds a greater sense of depth and luminosity. Further texture is created through *lifting*, *spattering* and *dry brush*.

Sumi-e ink wash comes out of the Japanese tradition, which is based on Chinese calligraphy. The medium requires precision and mastery of brush strokes to achieve variation in form and style [Hirayama 1979]. Holding the brush upright creates straight strong or fine lines, depending on brush pressure, and it also controls shading effects. A slanted brush creates heavy, broad strokes with a heavier ink flow, while a horizontal brush stroke yields an even larger painted area.

Additional effects include the *pause* in brush movement, which creates the distinctive end caps of a stroke, or using the *follow through* for a strong line that trails off based on pressure. Applying more pressure can create a blossom of ink, which can fill in a region with a solid ink presence, and the water saturation of the brush leads to gradient effects within a stroke.

We integrate the motions used for these watercolor and ink techniques in order to allow for artist exploration into analogous effects within the Fluid Brush medium. Such explorations with Fluid Brush led to the *soft* and *shading* effects, which accomplish similar goals to the *flat wash on wet paper* and *graduated wash* respectively, and the *blending* effect, which creates color and texture patterns reminiscent of both the *variegated* and *dry brush* techniques. Some artists drew on calligraphic techniques to emulate the *pause* and *follow through* effects using similar brush controls to generate Fluid Brush's *bleeding* and *calligraphic* effects. In the "User Reaction" section, we show the visual appearance of these techniques and how artists incorporated them into art made within the Fluid Brush system.

4 FLUID BRUSH SYSTEM

Working from a paint brush metaphor, an artist draws on the Fluid Brush canvas or imported image, creating particle effects that advect along the flow of the stylus stroke. To accomplish this, the system periodically records the position of the stylus while the stylus nib is in contact with the tablet. These points, or *touches*, are cubically interpolated to form a curve called a stroke, S, made up of *stroke segments*, s, that connects consecutive touches, t (shown in Figure 3). The stylus tilt angle, pressure and velocity are recorded and stored at each stroke segment, and these controls influence both touch radius, r_t, and segment density, ρ_s, which allows for variation in structure along the stroke.

Particles are added at random within each segment, where the maximum perpendicular distance is based on the neighboring touch radii, r_t and r_{t+1}, and they advect along underlying velocity fields. Particle movements are affected by both position on the underlying velocity fields and parameters of the *parent* stroke segment, s.

Since strokes are segmented, sections of the overall stroke can vary with the changes in brush motions. This mimics the principles of a paintbrush used in traditional watercolor and calligraphy, and to maintain this metaphor, we allow stroke speed to control the segment's laminar flow velocity field and stroke thickness, and pressure and tilt to modulate the segment's stroke width and density.

The underlying velocity field is a composition of two simpler fields: one dictating turbulent motion, and the other determining the speed and direction of laminar flow. This laminar flow is generated by the stylus strokes, which we treat as an equivalent to the binder material used in traditional painting. In the case of Fluid Brush, the particles perform a similar role to traditional paint pigment while the fluid motion is equivalent to the paint's binder that dictates how pigment advects along the canvas. The combination of small-scale turbulent effects within the artist-directed laminar flow allows artists to capture both stroke direction and feel, and the chaotic texture of fluid.

Such a model also avoids the complex GUI interfaces most particle control systems like After Effects [Adobe 2015] or Houdini [Effects 2015] require, allowing artists to create unique, fluid-like effects without a significant investment of time. These effects can be used directly in designs, animated enhancements to photographs and illustrations, mock-ups for prototyping more intricate effects, or as stand-alone art.

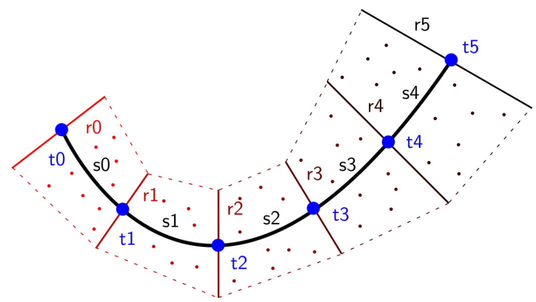


Figure 3: The stroke S consists of a cubically interpolated sequence of touches t and segments s. Particles generated in s are constrained within a perpendicular distance of the stroke width (r), which is linearly interpolated between segments, to create smooth variation in stroke width.

4.1 Strokes and Touches

Since a stroke S is composed of a sequence of touches generated as point samples during stylus movement, an uneven distribution of touches could slow performance or lead to visual artifacts. Thus we cull excess samples to create an even sampling. After this step, each touch has a distance from its neighbors of at least twice their combined radius, $r_t + r_{t+1}$, which avoids closely-packed touch segments and ensures a particle is within only one touch segment at a time.

This space also allows us to smooth S's line quality by further subdividing the stroke using cubic interpolation. We determine subdivision placement by ensuring each subdivision segment is about r distance from its neighboring touches. For example, in Figure 3, if t_0, t_2 and t_5 were the touches generated from the stylus, t_1, t_3 and t_4 would be created during the subdivision process at regular intervals. Just as the positions of additional touches are based on cubic interpolation, so are their segment parameters (shown in Table 1) to maintain a smooth, visually appealing line quality.

Particles are generated within each parent segment s based on segment density (ρ_s), which is the number of particles per pixel area. Particle position is assigned randomly within s's bounds, shown as the solid radius lines, and the dotted outer line in Figure 3.

4.2 Particles

Since we consider particles a form of pigment in Fluid Brush, each particle p has an associated shader texture and color value. These

Table 1: Parameters that influence stroke appearance are associated with either touches, stroke segments or particles. Some parameters are set upon stroke creation, while other parameters are updated at each time step of the simulation.

Parameter	Owner	Updated at time step
r	touch	no
ρ	segment	no
turb	segment	no
lam	segment	no
color	particle	no
texture	particle	no
$\vec{v}$	particle	yes
α	particle	yes

values are generated upon particle creation, and do not change during p's lifetime. Each p has velocity $\vec{v_p}$, which updates at each time step (see Table 1). The canvas' underlying velocity fields determine the updated values of $\vec{v_p}$, which in turn dictates how the particle flows along the canvas. We create per-segment parameters to act as velocity amplifiers for $\vec{v_p}$, which increase the turbulent and laminar flow (turb_s and lam_s) in order to give artists better control over the speed of the fluid. The particle's transparency, α_p, is based on its perpendicular distance from the stroke center. By fading out from the center of the stroke, Fluid Brush gives strokes a softer edge reminiscent of watercolor or ink wash.

4.3 Particle Flow Along Stroke

Constraining each particle p within its parent stroke segment, s, allows strokes to intersect and overlap without influencing the other stroke's density or flow patterns. This is not necessarily how a physically-based medium like watercolor works, but we found that separating strokes led to interesting visual effects, as strokes better maintained their initial form.

We enforce this constraint by keeping p within the outer edges of s, and repositioning the particle if it exceeds those bounds, but we allow p to leave s if it flows into neighboring touch segments along parent stroke S. This movement between segments is critical for depicting strong laminar flow, where particles advect along the entire length of stroke S. Without this reparenting step, the particles have visibly choppy movements.

Yet even if p lies beyond the endpoints of s, we cannot assume it has moved to an adjacent segment. At higher laminar velocities, it is possible a particle will move through multiple segments within a single time step. Therefore it is necessary to search segment by segment until we find the appropriate segment s_{new} for reparenting p: the segment that contains p, and is the closest segment to s based on position along the stroke, rather than Euclidean distance.

This segment by segment check ensures a consistent flow along S regardless of a stroke's self-intersections, which occur when the artist loops or crisscrosses a single stroke. We must also consider particles in the stroke's end segments. To avoid particles clumping at the end segments of S, when p exceeds that segment's bounds, we reposition p at random along S.

4.4 Multiple Velocity Fields

Fluid Brush maintains multiple underlying velocity grids to separate the calculations for the turbulent field from the laminar flow field. These vector fields are then combined (as illustrated in Figure 4) to influence $\vec{v_p}$ for each particle. Particle positions are then updated using forward Euler time integration.

This technique of combining fluid flows allows artists to use stylus movements to influence the rate of laminar flow independent of the turbulent effects, and even with just two flow patterns, Fluid Brush captures a broad range of fluid motion effects. The laminar field incorporates the directionality of each brush stroke into a smooth, coarse flow, while the turbulent field models small-scale turbulence and chaotic motions. Since artists can see the immediate effect of their brush movements on the visual output, and they do not need to consider the turbulent flow directly, artists avoid having to consider the underlying physics. This keeps concepts of fluid motion intuitive to non-expert users.

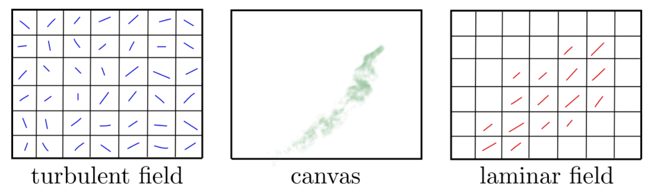


Figure 4: The drawing canvas has multiple underlying velocity fields. The laminar field captures directional flow introduced by the stylus strokes, while the turbulent field generates randomized turbulent patterns.

4.5 Laminar Field

Laminar flow is a natural fit for a brush metaphor, as brush strokes have an implicit sense of direction based on their start and end positions. A number of traditional media convey a sense of brush motion through stroke technique, but with a digital medium like Fluid Brush, we make this motion explicit through our laminar field.

When the artist places a stroke on the main canvas, the laminar field is updated in three steps, shown in Figure 5.

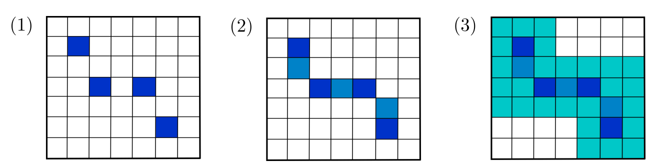


Figure 5: Laminar vector field modifications: 1) introduction of stroke velocities (dark blue) from the touch 2) interpolation of stroke velocities (light blue) between vector grid cells and 3) iterative diffusion (cyan) to surrounding grid cells.

In the first step, we map the stroke velocity, $\vec{v}$, which is based on the speed and direction of the stylus, from the touch position on the canvas to the corresponding grid cell in the laminar field. We apply the segment's velocity amplifier, lam_s, to give artists additional control over the speed of the laminar flow.

For the second step, we cubically interpolate these values to the grid cells between touches, generating an unbroken series of updated cells along the center of stroke S. These cells contain the interpolated velocities of $\overrightarrow{v}$ to create a smooth transition between stroke velocities.

In the final step, we diffuse these updated cell values, relaxing $\overrightarrow{v}$ to neighboring cells using Laplace's equation, $\nabla^2\varphi = 0$, where φ is velocity. This diffusion is restricted to the stroke's area, since a global diffusion would continue to dampen the velocities of previous strokes as new strokes are added. Limiting diffusion to the area of a new stroke allows overlapping strokes to interact (similar to how paint from multiple strokes mingle on a physical canvas), but without causing changes to non-overlapping strokes, which would be unintuitive to the artist.

At each iteration of this relaxation, we take a first pass through the grid cells to flag the neighboring cells (in all eight directions) in addition to the cells already influenced by the stroke's velocities. We then calculate the diffusion of the cell velocities across only the flagged cells (shown in Figure 6) until the diffusion reaches the edge of the stroke.

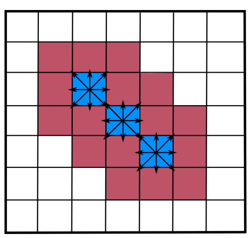


Figure 6: The relaxation process is limited to the "flagged" cells: cells influenced by the current stroke's velocity (blue) and their neighbors (red).

4.6 Turbulent Field

For the turbulent field, Fluid Brush uses Bridson's curl-noise technique [Bridson et al. 2007]. This results in a divergence-free velocity field, used in a similar fashion by Smoke Brush [Abraham and Fussell 2014]. Curl-noise is not a physically-based fluid simulation technique, but the velocity vectors it generates resembled the flow patterns of turbulence.

Curl-noise uses Perlin noise to model a potential field Ψ. By taking the curl of Ψ, we generate a turbulent velocity field that remains smooth. This allows for fast fluid effects, and we can use our segment's parameter control $turb_s$ as Ψ's length scale. By also applying $turb_s$ to amplify $\overrightarrow{v_p}$, we adjust the particle's final velocity based on both the underlying grid and the speed of the turbulence within the stroke segment, allowing for a range of turbulence patterns within each stroke.

4.7 Shaders

Fluid Brush provides a color palette and three built-in particle shaders for the rendering of the particles. These custom shaders are *wispy* (used in **Warrior**), *bubbly* (used in **Beer**), and *starry* (used in **Unicorn**), but this selection of shaders, and additional affects such as color and alpha variation or additional types of fluid shaders, can be easily extended or added using GLSL.

4.8 Seamless Animated GIFs

To produce an artifact usable outside of Fluid Brush, the system captures frames to create short animations, or cinemagraphs. This artifact must seamlessly loop to give a sense of continuous motion, but since the only animation in these sequences is particle movement, we do not need to employ more expensive (or extensive) methods such as those described in the survey paper by Bénard et al [Bénard et al. 2011].

Instead we created a simple technique of temporally shifting each particle's motion during the captured frames by a random amount (see Figure 7). This conceals the starting and stopping position of the individual particles, since each particle's capture loop begins and ends in different frames within the animation. Thus the particle system as a whole appears to have continuous motion despite the individual behaviors of the particles, leading to animation sequences that can be looped indefinitely.

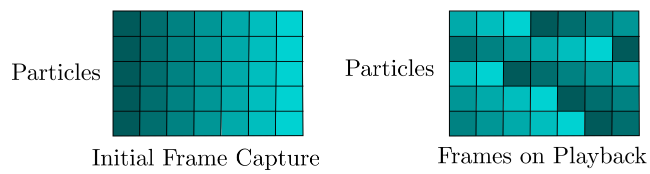


Figure 7: A random temporal offset within each particle's frame capture creates a sense of continuous fluid motion.

5 USER CONTROLS

Implicit stylus controls allow for stroke dynamism typical to traditional watercolor and calligraphy, as discussed in the Design Study. Without these stylus controls, stroke variation isn't possible, which limits both the types of brushwork, and complexity of particle movement. The difference in fluid and brush quality via stylus control is demonstrated by Figure 8.

5.1 Stylus Controls

Fluid Brush's stylus input uses the brush control concepts of watercolor and calligraphy to adjust its parameters via stylus pressure, tilt, and velocity. Such controls are inspired by traditional painting models, where greater brush pressure provides greater pigment density and a wider radius. The tilt mechanisms take inspiration from sumi calligraphy, where the artist uses brush angle to modulate stroke density, with greater brush angle creating greater ink flow (or pigment density).

The brush stroke's velocity influences the stroke's width similar to a traditional brush. This differentiates between faster, sketchier strokes and slower, robust strokes. The parameters, $turb_s$ and lam_s, increase with stroke velocity, which creates a greater sense of motion in fast strokes. We made this design decision as artists often use faster brush strokes to convey liveliness and sense of motion in traditional media.

Figure 8 shows how the individual and combined types of stylus inputs modifies the stroke's quality. With no stylus control, an artist has relatively little control over variation in the stroke. By adding stylus tilt or stylus pressure, an artist obtains better manipulation of stroke density and form, leading to variations similar to those seen in traditional painting. Stroke density and form can also be controlled by stylus velocity. To create the stroke example "stroke velocity stylus control" in Figure 8, the artist used a slow brush speed for the wider part of the stroke before accelerating into a final, fast motion to draw the stroke's tail. This results in the start of the stroke maintaining a wispier appearance with slower motion that thins into a denser line with a faster rate of flow.

By combining all three controls into the stroke, we obtain an overall better line quality while still allowing for variation in brush movements and flow speeds. Such brush-based movements can achieve a wide variety of stroke appearances, and Fluid Brush is designed to be adaptable, accommodating how an individual artist wishes to depict, and interact with, the medium's features. Control details are available in the Appendix.

While Fluid Brush emphasizes a paintbrush interface to minimize explicit artist controls and interface, we still included a GUI for some high-level controls, similar to how in traditional media, an artist can select a brush by type and size. We included sliders for Stroke Width, Turbulence Speed and Directional Speed. Stroke Width adjusts r_t to determine the width of the stroke segment. Turbulence Speed affects turb_s within the turbulent field, such that a higher value creates faster, more distinguishable curl effects, whereas a lower value results in slower, less chaotic patterns. Directional Speed provides an amplifier, lam_s, for the laminar flow velocity vectors.

6 USER REACTION

The purpose of Fluid Brush is to explore accessible interfaces within the area of new artistic media, so we demoed Fluid Brush to three groups: members of an Autodesk Animation User Group Association chapter, designers at a design firm, and comic artists from a sketch group. Fifteen users gave us informal feedback, including technical artists, designers (who may not have an art background), and traditional artists.

We asked users to try Fluid Brush, and create an artistic artifact if they felt inclined. The goal of this was to determine whether artists would identify effects within the Fluid Brush system that are 1) reproducible, 2) visually distinctive from effects in existing media, and 3) aesthetically compelling.

In addition to the basic modes of interaction (e.g. line work incorporating turbulent and laminar flow), we noticed different artists discovered different effects. This matched our intention that Fluid Brush should support non-digital artists as they experiment with the medium as they would physical paint. These effects, which seem analogous to traditional paint media, are listed below, displayed in Figure 9, and looping animations are available in the supplemental material.

(a) The *soft* effect is achieved by stippling the stylus brush with a wide radius brush. This creates a broad, foggy line quality, similar to a watercolor *flat wash*, which Fluid Brush artists used for a subtle background effect.

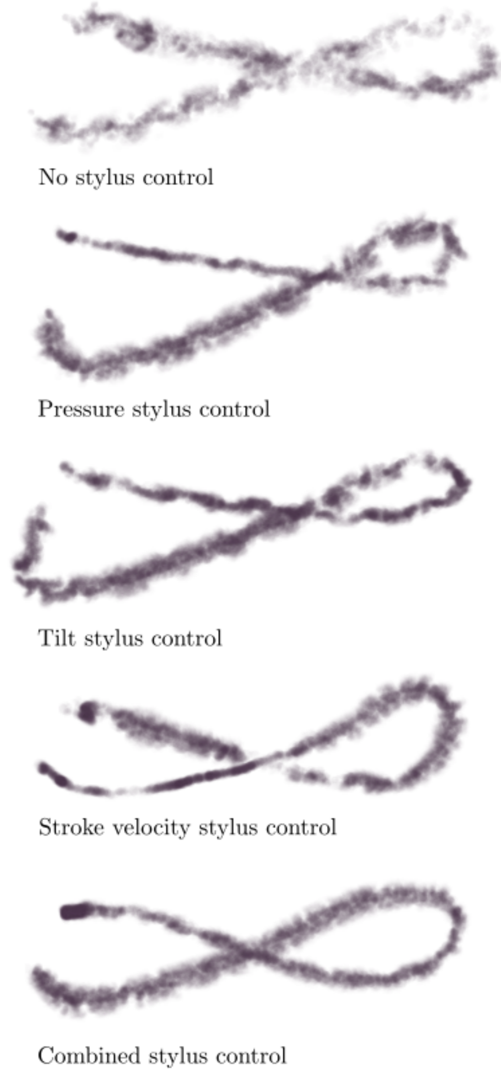


Figure 8: The range of stylus controls based on pressure, tilt and brush stroke velocity, as well as a combination of these stroke controls.

(b) The *calligraphic* effect is achieved by varying pressure, tilt, and sometimes stroke velocity, to achieve a greater range in stroke width and particle speed within a single stroke. This allows for the calligraphic *follow through* effect, which adds dynamism and weight to Fluid Brush line work.

(c) The *shading* effect is achieved by reducing stylus pressure as the brush moves out from the point of origin. Toward the edges, the artist applies individual dots of fluid pigment for a soft edge. Turbulent particle motions blend these strokes, similar to *gradient wash* in watercolor.

(d) The *blending* effect is achieved by overlaying strokes from multiple brush types to create a unique set of textures and flow

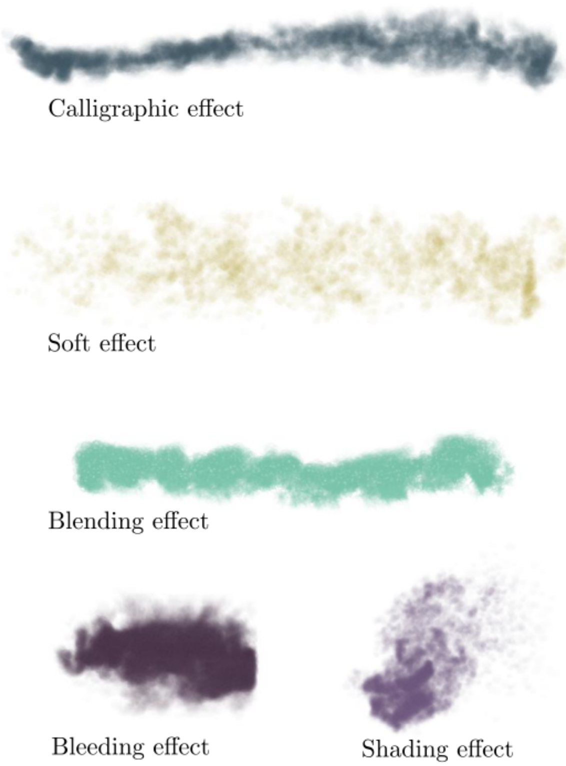


Figure 9: Effects in the Fluid Brush medium demonstrate the range of techniques artists discovered and used to create artwork in the Fluid Brush system.

patterns. This is similar to *dry brush* in watercolor for creating variation in stroke texture.

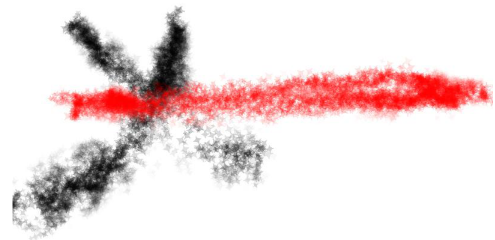
(e) The *bleeding* effect is achieved by applying a stroke with a strong angle of tilt over itself. This creates a high particle density along the middle region of the stroke, emulating the *pause* in ink-painting, while the feathering particles resemble *wet into wet* from watercolor.

6.1 User-generated Results

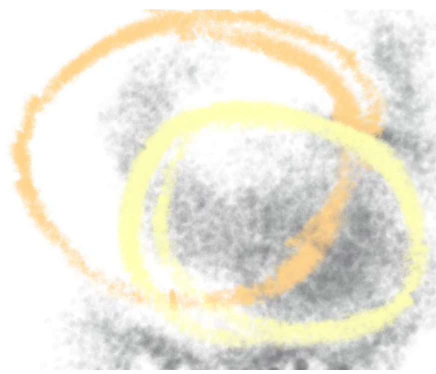
Logo and **Unicorn** demonstrate strong *calligraphic* effects via pressure and tilt to generate variation in line quality. **Ghost** takes a painterly scene, and uses *soft* strokes for the twinkling stars, while relying on more typical laminar strokes to generate swirling fog.

Warrior uses multiple *shading* strokes to create a smoky, magical enhancement to the existing image, whereas the **Witch** uses a single brush stroke with high laminar flow to create a trail of magic.

Rings uses *blending* by combining multiple shaders, colors, and turbulent/laminar motion to create a highly textured, abstract image. **Bamboo** relies almost entirely on *bleeding* to create the bold, segregated lines of the bamboo stalk. This emulates the *pause* used in ink painting to create the hard, stylized edges of this traditional painting subject.



Logo: A graphic design experiment incorporating Fluid Brush effects into commercial logos © Umy Boonmarlart.



Rings: An abstract work that uses blending effects to create a highly textured image © Chelsea Hostetter.

Bamboo: A stylized work that uses the bleeding effect to emulate the ink brush style found in calligraphy painting © Evan Kight.

The artist of **Silos** had no prior experience with a tablet or stylus, but she understood the high-level elements of both the stylus and our system's controls within minutes of experimentation. She added roiling, turbulent clouds of fluid to enhance her existing artwork.

Silos: A pencil-and-photograph landscape enhanced with animated storm clouds using Fluid Brush © Katie Maratta.

Waterfall: A photograph enhanced with both laminar and turbulent flow © Matt Swarthout.

Warrior: A digitally colored warrior enhanced with shading fluid effects to create the impression of smoke © Lauren Liebowitz.

Witch: A digitally colored witch drawing enhanced with flowing magic from her wand © Katie Bauer.

Ghost: A painterly image using the soft effect for the twinkling stars, and a strong laminar effect for the rotating smoke © Evan Kight.

Unicorn: A Fluid Brush drawing that emphasizes calligraphic strokes © Evan Kight.

Beer: A photograph enhanced with rising bubbles © Sarah Sansom.

Several of the artifacts come out of the cinemagraph tradition of enhancing still photographs with subtle movements to create a unique blend of static and animated effects. **Beer** uses strokes with low turbulence but medium laminar flow to create the impression of bubbles rising. **Waterfall** uses laminar strokes along the falling water, and *soft* strokes for the frothing foam at the bottom. There is some *blending* as the wispy and bubbly shaders interact. For a full demonstration of these effects and looping animations, see the supplementary video and materials.

Generating these artifacts took no more than a couple minutes, but the users often experimented with the range of effects displayed in the GUI interface before focusing on a single piece. Having tested a range of stylus techniques and GUI parameter settings, they then spent considerable time and effort to recapture the effects they found appealing.

In terms of artist response, technical artists expressed particular interest in using Fluid Brush as a tool for creating fast background effects in games, such as looping billboard animations. A common sentiment among designers was that the easy generation and control of this sort of fluid effect could make interesting website effects for clients. One designer with experience in After Effects commented that the *"draw first"* nature of Fluid Brush is highly intuitive compared to the workflow of After Effects.

In the case of traditional artists, the medium allowed them to experiment with digital media using a simple paint brush interface. Since they received immediate, visual feedback based on their strokes, the artists were able to quickly understand and manipulate the fluid motion to create a variety of animations. Given this level of accessibility, we believe other new digital media can be made more accessible through the use of proper design metaphors when creating artist tools and interfaces.

7 LIMITATIONS

More advanced artists, particularly from the digital art community, expressed interest in a wider range of features and functionality, including image-masking to preserve particle-free areas, and layering for greater control over particle "depth" in a scene. A number of users also wanted the ability to modify touch parameters and placement after a stroke's creation.

All of these features are readily extensible, but we do not include them in the stand-alone version of Fluid Brush, as it's intended to replicate the simplicity of a traditional brush-based medium. We propose maintaining this simple system for traditional and hobbyist artists but provide a separate plugin for a VFX/animation pipeline to give technical artists a wider range of controls.

8 FUTURE WORK

Fluid Brush uses the interactions of traditional art tools in the space of new artistic media. This makes digital media accessible to artists from a traditional background, but there is much room for exploration. In order to examine how traditional brush controls can work in a more complex system designed for experienced artists, we intend to integrate Fluid Brush into a system like Houdini or After Effects. We believe Fluid Brush's simple interface for controlling fluid motion will make such tools more accessible to new users and provide a better way for more experienced digital artists to prototype ideas. This would provide a larger range of control across the interactive spectrum, as discussed by Isenberg on the ideal direction of interactive tools in non-photorealistic rendering [Isenberg 2016].

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APPENDIX

Equation 1 shows how stylus pressure (ψ), and tilt influence (θ) modulate ρ_s, or particle density within segment s. Equation 2 shows the calculation for r_t, or the radius of touch t, which is influenced by the stylus pressure, tilt, and stroke velocity magnitude (v).

Values $\min_\rho$, $\max_\rho$, and $\min_r$ are constants in the system, and they determine the maximum and minimum density, and minimum radius of influence. The value, r, is the adjustable radius set by the Stroke Width slider.

For ψ, θ, and v, we normalize the magnitude of the stylus input, and apply the logistics function shown in Equation 3, where x is the normalized stylus input, and b and k are constants. We chose a logistics curve, because its property of slow initial, and slow mature growth reduces sudden, unintended changes in stroke appearance, while the curve's exponential shape in the middle allows for deliberate variation.

$$\rho_s = \min_\rho + \max_r(0.5\psi + 0.5\theta) \tag{1}$$

$$r_t = \min_r + r(0.6\psi + 0.3\theta + 0.1v) \tag{2}$$

$$f(x) = \frac{1}{1 + b\mathrm{e}^{-kx}} \tag{3}$$