PencilSketch — A Pencil-Based Paint System

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Abstract

An artist, when using a paint system, has a conceptual model of the painting surface, of the colouring agent, and of the applicator with which the colouring agent is applied. These models, often based on physical analogues, guide the artist in both his use and his expectations of the system. We discuss several of the models that underlie available systems and introduce the pencil, paper, and eraser model of PencilSketch. The design and implementation of PencilSketch are described as well as a mouse-based virtual 5-D tablet, developed for the system.

Résumé

L'artiste qui utilise un système de dessin assisté par ordinateur a un modèle conceptuel de la surface de dessin, de l'agent de coloration et de la technique d'application. Ce modèle dont l'artiste se sert pour comprendre et prédire le fonctionnement du système est souvent basé sur un système déjà connu par l'usager. Nous allons examiné les modèles de quelques logiciels avant de présenter le modèle de PencilSketch: crayon, papier et gomme à effacer. La conception et la réalisation de PencilSketch et d'un système capable d'imiter les capacités d'une tablette graphique cinq dimensions seront décrit.

Introduction

An artist's choice of medium, whether he uses acrylics, pastels, charcoal, or oil, is as fundamental in the creation of each work as is his choice of subject. Computer paint systems can be thought of as yet another medium with which an artist might express himself, but, on closer analysis, one sees that these systems vary greatly. These differences can often be traced to the conceptual model used in their design. A colour airbrush-emulating package is similar to a charcoal sketch system only in that they both provide computer-based facilities with which one may paint images. The tools, the feel, and the resulting images are not the same.

PencilSketch, developed at the University of Waterloo, illustrates the results of rigorously applying a conceptual model for each of the conceptual objects required by a paint system. The painting surface is modelled as a sheet of paper, the applicator is a pencil, and the colouring agent is a pencil lead. While these models comprise an easily understandable base, they can be extended beyond the capabilities of their real-life counterparts.

The paper presents a detailed discussion of the conceptual objects used in PencilSketch illustrating how they have been used in earlier paint systems. This is followed by details of the models used to implement these objects, the paper model, the pencil model (including a description of a mouse-based virtual 5-D-tablet that allows one to control pencil pressure and tilt) and the model of the pencil lead.

Conceptual Models

To use any interactive system the user must have a conceptual model of the objects with which he interacts. Is he changing ASCII characters in a text file or editing text on an abstract piece of paper? Providing models that are more real from the user's point of view, even though more abstract for the implementor, (such as a piece of paper or a file folder rather than a text file or a directory), significantly reduces the training time, and, perhaps more importantly, reduces the user's inhibition about using and exploring a system.

However, as Smith points out, sticking completely to a metaphor can cripple a system's functionality [Smi87]. He differentiates between the learnable *literal* features and the *magical* features that increase a system's functionality beyond that of the physical analogue.

Paint system metaphors cover three areas. The artist requires a conceptual model of the surface on which he is painting, the properties of the colouring agent he is applying to the surface, and the applicator or brush with which he is carrying out this operation. Looking at the conceptual objects — surface, applicator, and colouring agent — in turn, one finds a number of models that have been or could be used for each.

Surface

Often the implementor's conceptual model of the painting surface is the frame buffer. Such a model has led to the implementation of a large number of painting tools — hue paint, value paint, fills — that fall out naturally from this model. However, it has not been an easy model for the artists. In a series of BBC television programs showing artists using the Quantel Paint Box [BBC87], a highly developed paint system, users perceive that they are doing something akin to painting on glass where the applicator is a brush and the nature of the colouring agent is not apparent although it seems to share some characteristics with water paint. The artists realize that they are not spreading paint on the face of the CRT, but somehow the process makes them feel that they are. Indeed, the series of programs is entitled "Painting on Glass".

The glass metaphor, while easy to grasp and pleasing to use, appears to affect the way artists paint. Broad strokes, little or no texture, and bright or pastel colours dominate.

The only other surface model of which the authors are aware is that of paper used in both GWpaint (see below) and PencilSketch. The advantages of using paper as a surface model are user familiarity and simplicity.

A valuable extension to any surface model, suggested by Wallace [Wal81], is that of stacking the surfaces, like the cels used in animation, and defining an opacity component for each pixel. This opacity determines how much of the surface image at the lower level shows through to the final displayed image. The implementation of Palette by Higgins and Booth has a foreground and background image where the mix of foreground and background colour for each pixel is determined by the pixel opacity [HB86]. This model led to the extension of the painting tools to support painting into this opacity layer to render areas of the surface more or less opaque.

A second surface model extension used in several systems is that of a protecting mask. Such a mask is applied over a surface to inhibit painting onto that area of the surface.

Applicator Models

Three applicator models have dominated paint systems — the rubber stamp, smooth paint, and the airbrush. Rubber stamping is simply the addition of a predefined image to the surface at the locator position in response to a locator button push. Smooth paint is the continuous addition of a predefined image to the surface at the locator position while the locator button is pushed. The term airbrush has been used loosely to define an extension to continuous paint where the resulting image is some function of the airbrush colour, the surface colour, and some opacity control. Rather than painting an area red, an airbrush might just add a touch of red.

One of the more interesting applicator models is the charcoal sketching facility of GWpaint [BSM88], [Sil86]. The implementors have modelled the applicator as a piece of charcoal. Of course the effect of charcoal stroked on paper depends on how it is held — its angle with respect to the surface, the shape and size of the piece of charcoal, and the pressure with which one applies it to the surface. To handle these parameters, a GTCO 5-D tablet was used which provides, in addition to the X,Y location, values for the pen pressure, the pen tilt, and the direction of that tilt.

Colouring Agent

The colouring agent can be the bright water paint that many paint users imagine they are using, agents that affect only the brightness of the surface (value paint) or the hue of the surface (hue paint). Charcoal is the user's conceptual model for both the applicator and the colouring agent in GWpaint.

The model used for colour selection or manipulation appears to have a significant effect on the colours used in a system. Most paint system colour mixing tools are based on an additive colour model (which is more appropriate for mixing coloured lights) rather than a subtractive colour model that relates more closely to the actual process of mixing paint. An informal study of the use of a subtractive-colour paint mixing tool has shown that artists tend to select darker or more sombre colours [Nee89].

PencilSketch Model

The design and implementation of PencilSketch was an exercise in taking a conceptual model, studying it, then implementing a paint system based as solidly as possible on it. A study of several books on the use of the pencil [Cal74], [Gup77], [Ruf69] indicated that artists require the following components in a pencil sketching system:

- A selection of pencils. The hardness of the pencils should vary from 2H to 6B and there should be a variety of lead shapes and sizes available.
- The ability to hold the pencil at different angles, and to use different pressures, is useful in producing different shades of grey and qualities of tone.
- The ability to use a variety of strokes. Long flowing strokes are often used for drawing backgrounds and indicating simplicity, while series of short strokes are useful for indicating texture.
- An eraser should be available. The eraser should work cleanly without smudging.
- An erasing shield would be convenient. This protects work that you do not want to have erased.

Each of the conceptual objects was considered independently.

- The Paper

  The type of paper used in sketching can affect the appearance of a sketch to a greater degree than the pencil used [Ruf69]. A pencil leaves a mark on a page due to friction between the pencil lead and fibres in the paper. This friction bites graphite from the pencil and leaves it behind on the page in a pattern dependent upon the texture and roughness of the paper. The paper currently modelled in PencilSketch is completely smooth, yet its fibres bite off graphite easily, producing perfectly smooth tones with no grain. Such a surface is not physically attainable, but is most closely approximated by bristol, a board of laminated sheets.

  An appropriate extension to PencilSketch would be the implementation of a paper model with variable parameters for the texture and roughness. The range of these parameters should permit the use of papers unattainable in real life.

- The Pencil

  The pencil is the applicator used in making pencil sketches. The amount of graphite applied to the page by a pencil is determined primarily by the pencil lead's hardness. Pencils are graded in seventeen degrees of hardness from 9H to 6B; 9H are the hardest pencils and 6B the softest. The hardness of the lead determines the darkness of the tone, the softest leads produce the darkest tones. PencilSketch pencils are available in a much wider range of hardnesses than real pencils! Our pencils vary continuously in hardness from 0 to 1, 0 is a lead so hard it leaves no mark, and 1 is the softest lead available.
  Pencils are available in a variety of forms; the most common being the familiar wood and graphite pencil with a conical tip. A simple pencil can be used to create a variety of effects by varying the pressure and tilt used in the stroke. For example, by holding a fairly hard pencil close to horizontal and stroking lightly first one way then the other a very subtle shading can be produced. By holding the same pencil vertically and pressing harder outlining can be done. In addition to common pencils, artists often use graphite sticks and pencils with chisel shaped tips. These are used to create wide flowing strokes, and can add a sense of direction or motion to a sketch.

- Erasers

  Good artists use an eraser infrequently, some abstain completely from its use. Erasers are not optimal tools; they smudge the work and change the quality of the paper so that it is difficult to draw on again. For this reason, the eraser is the one part of the pencil drawing metaphor that has been substantially altered in PencilSketch. Smudging and paper tearing are both undesirable aspects of erasing, so the eraser modelled in PencilSketch does neither.

  The PencilSketch eraser is a graphite removal device with no side effects. Different grades of erasers have been provided. Each grade removes a different amount of graphite from the page, just as different grades of pencils add differing amounts of graphite to the page. In fact, the eraser model is exactly symmetrical to the pencil model. The pencil is a graphite applicator, in exactly the same way, the eraser is a graphite remover.
  Arguably, it is desirable to add a real eraser to the conceptual model, since occasionally artists will take advantage of the smudging that erasers produce. A similiar but distinct tool would be a smudging stick. This would not remove graphite as would the eraser, but would move it around on the paper.

- Graphite

  The colouring agent modelled in PencilSketch is graphite. The darkness of the sketch at any point is determined by the amount of graphite on the page at that point. The paper is initially void of graphite and is white. As graphite is applied the darkness increases until the maximum allowable density of graphite is on the page. The point on the page is now completely black. Sketches are

created by changing the distribution of graphite over the page.

- Other tools

  There are a number of other tools used by pencil artists that have not been incorporated into the conceptual model. Some, such as fixatives to keep the finished work from smudging, are unnecessary. Others, such as erasing shields, have been left out to simplify the model.

Implementation

The state of the PencilSketch image is completely determined by the distribution of graphite over the page. This information is stored in a frame buffer. Thus by keeping the state of the image up to date, the image on the screen is automatically kept up to date as well, providing the artist with continuous feedback on the image he is creating. Often with large pencils and graphite sticks the computer cannot update the frame buffer as quickly as the artist applies the pencil, and so the artist "gets ahead of" the display.

A pencil darkens the page by applying graphite as the pencil is moved. Each time the pencil moves a distance of one pixel, a certain amount of graphite is added to the page by each point on the pencil lead which is contacting the page. The amount of graphite added by any point on the tip of the pencil depends on five parameters:

1. The amount of graphite already on the page, g_0.
2. The hardness of the pencil, h, $0 < h <= 1$. This determines the range of darknesses for which the pencil is optimal.
3. The pressure being applied to the pencil, p. This influences how close to the maximum possible darkness the pencil draws. The pressure is measured on a scale from 0 to 1.
4. The "lead function" $b(x, y)$, analogous to the brush functions used in other paint programs. This parameter varies over the part of the lead which contacts the paper; it gives the pencil line a characteristic look and shape. The lead function is defined to match the characteristics of the lead when the pencil is held vertically.
5. The tilt of the pencil. This is used to distort the lead function for a vertical pencil, $b(x, y)$, into the lead function for a tilted pencil. This is done by scaling and rotating the domain of $b(x, y)$ as discussed below.

The amount of graphite added to the page as the pencil moves one pixel is:

$$g_{\text{added}} = b * p * h * \frac{1 - g_0}{1 - \left(1 - \frac{1}{h}\right) g_0}$$

For a given hardness, pressure, and lead function evaluated at the current point, the amount of graphite added is a function only of g_0, therefore in implementation many of the terms can be precomputed before applying a specific lead to the page. The function was chosen to satisfy the following critera:

- For a given amount of graphite on the page, the amount added should vary linearly in pressure and brush function value.
- If the page was saturated with graphite, then no more would be added. That is, if $g_0 = 1$, then $g_{added} = 0$.
- If there was no graphite on the page, the amount added should vary linearly with pencil hardness.
- When a small amount of graphite is added to a blank page, the amount of graphite added to the page decreases by that amount. Mathematically, we want $\partial g_{added} / \partial g_0 = -1$ at $g_0 = 0$.
- The amount of graphite added should always be positive.

The function given above is a simple function which satisfies these criteria.

When the lead function, $b(x, y)$, is used in the above equation, it is sampled in a manner dependent upon the tilt of the pencil. Define the lead function for a vertical pencil as $b(x, y)$, and let $b(x', y')$ be the lead function for the same pencil when held at a tilt of magnitude α and swivel angle of θ. The x', y' coordinates are obtained by first scaling and then rotating the x, y coordinates. First, the following transformation is applied to x to account for the magnitude of the tilt:

$$\overline{x} = \begin{array}{c} x, x < 0 \\ k\alpha x, x > 0 \end{array}$$

where k is a constant which depends on the particular pencil being used. Thus, the tip is modelled as changing only in the direction tilt is being applied. Now, the coordinates $(\overline{x}, y)$ are rotated by θ to get the coordinates (x', y'). To obtain the brush function at a point on the tilted lead (x', y'), apply the inverse of the transform described above to get a point on the vertical pencil, and then sample $b(x, y)$.

Each different pencil has a specific lead function associated with it. The lead function varies in shape and distribution to give each pencil a unique character. The standard pencil with a conical tip is modelled to have a circular domain with the values decreasing linearly from

the centre of the domain to the edge. Chisel shaped leads, graphite sticks, and even broken (two pointed) pencil leads can all be modelled using this technique.

While drawing in PencilSketch, lines are made continuous while the stylus is being held down. To do this we linearly interpolate between locations given by the tablet. We also interpolate between reported tilts and pressures giving a completely smooth variation of stroke.

In the design stage it had been noted that a pencil artist holds the pencil at different angles and with varying pressure to achieve various effects. This is simulated through the use of a GTCO 5-D tablet (where the five dimensions are x, y, pressure, magnitude of pen tilt, and direction of pen tilt). This was the approach successfully implemented in the charcoal sketch system, and it is an approach that fits in well with our conceptual model. However most systems do not have access to such a tablet so it was decided to provide a mouse-based device that, as closely as possible, could accomplish the same function.

The mouse-based virtual 5-D tablet consists simply of a mouse, that provides the x, y components of the 5-D value, and a graphical dialogue box that provides the other three components. As can be seen from Figure 1, this dialogue box consists of an image of the pen plus a slider to set the pen pressure. The top end of the image of the pen may be grabbed and moved changing both the tilt and swivel angles. (In addition to these controls for the three dimensions of the virtual tablet, the dialogue box also contains the control for selecting a pencil or eraser, and setting the hardness of the pencil).

While this virtual 5-D tablet does permit control of all the dimensions required for pencil drawing using the inexpensive and ubiquitous mouse, the ability to modify the orientation and pressure settings while drawing is a serious loss. An alternative approach would be to provide dials to control the pencil pressure and/or its angle as suggested by Hill [Hil86].

Future Directions

There are two directions in which PencilSketch can be extended: improving the interaction and improving and extending the underlying conceptual model. There are many conceivable ways to control the virtual 5-D tablet; implementing several and letting users experiment with and comment on these would perhaps lead to a better interaction. The pencil, paper, and eraser models could be extended to allow textured paper. Also an extension to coloured pencils and paper would be interesting.

Conclusion

PencilSketch is an example of a paint system built around a specific strong model, and so provides a tool whose power is immediately obvious to the most casual user. The literal metaphors of the paper surface, and the pencil with the various leads, are extended by the magical metaphors of the perfect eraser and leads of extreme hardness or softness. In a limited way, it implements the power of a 5-D tablet on the mouse to control pencil angle and pressure.

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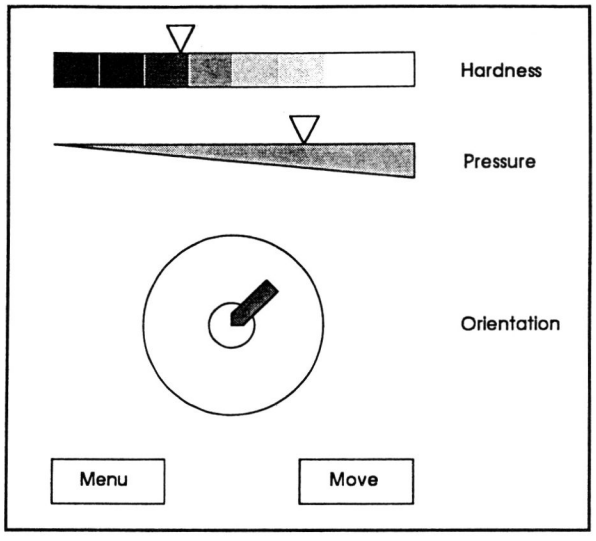

Figure 1. Panel used for mouse-based virtual 5-D tablet.

Figure 2. Sample PencilSketch drawing (artwork by Maureen Stone)