Observational Model of Blenders and Erasers in Computer-Generated Pencil Rendering

Mario Costa Sousa John W. Buchanan †

Department of Computing Science
University of Alberta, Edmonton, Alberta, Canada
{mario,juancho}@cs.ualberta.ca

† Also Research Scientist at Electronic Arts Inc.
Burnaby, British Columbia, Canada
juancho@ea.com

Abstract

In this paper we present a blender and eraser model that extends our graphite pencil and paper model. This blender and eraser model enhances the rendering results producing realistic looking graphite pencil tones and textures. Our model is based on observations on the absorptive and dispersive properties of blenders and erasers interacting with lead material deposited over drawing paper. The parameters of our model are the particle composition of the lead over the paper, the texture of the paper, the position and shape of the blender and eraser, and the pressure applied to them. We demonstrate the capabilities of our approach with a variety of pencil swatches and compare them to digitized pencil drawings. We also present automatic and interactive image-based rendering results implementing traditional graphite pencil tone rendering methods.

Résumé

Cette oeuvre presente un modele de gommes a effacer et de mélangeurs qui augmente notre modele de crayon a mine et de papier. Notre modele de gommes et de mélangeurs nous offre des images et textures plus réalistes. Notre modele est basé sur des observations de l'interaction de l'absorption et dispertion des gommes et des mélangeurs avec la mine de crayon déposé sur le papier. Les parametres de notre modele sont la composition des particules composantes de la mine de crayon, la texture du papier, la position et la forme de la gomme et du mélangeur, et la pression avec lequels ils sont appliqués. Nous démontrons les capabilités de notre aproche en comparant des traits dessinés avec notre systême avec des traits dessinés sur papier. Nous présentons aussi des images créés automatiquement qui démontrent la possibilité de créer des images usant des techniques traditionnelles d'illustration au crayon.

Key words: Non-Photorealistic Rendering, natural media simulation, tone and texture, pencil rendering, image-based rendering, illustration systems.

1 Introduction

The display of models using highly realistic illumination models has driven much of the research in computer graphics. Researchers in non-photorealistic rendering (NPR) seek to provide alternative display methods for 3D models or 2D images. In particular, recent work has focused on the modeling of traditional artistic media and styles such as pen-and-ink illustration [17, 10] and watercolor paintings [2, 11]. By providing rendering systems that use these alternative display models users can generate traditional renderings. These systems are not intended to replace artists or illustrators, but rather to provide a tool for users with no training in a particular medium, thus enabling them to produce traditional images.

In this paper we present results from our research in pencil illustration methods for NPR [13, 12]. We chose pencil because it is a flexible medium, providing a great variety of styles in terms of line quality, hand gesture, and tone building. It is excellent for preparatory sketches and for finished rendering results. Pencil renderings are used by many people in different contexts such as scientific and technical illustration, architecture, art, and design.

This paper presents extensions to our pencil and paper model [13] including supplementary pencil drawing materials with absorptive and dispersive characteristics. We developed an observational model for blenders and erasers. These tools can aid in the use of pencil and further enhance the rendering results.

The pencil and paper model [13] and the model presented in this paper can be adapted to existing interactive illustration systems [10, 15] and 3D NPR systems for technical illustration, art, and design [3, 17, 4, 7, 5]. We have adapted our models to render 3D objects automatically using traditional pencil illustration and rendering methods [12].

1.1 Related work

Our blender and eraser model is based on their absorptive and dispersive properties of deposited lead material (graphite, clay, and wax particles) on drawing paper. Previous work on pencil simulation has not addressed any of these issues. Vermeulen and Tanner [15] introduced a simple pencil model as part of an interactive painting system that does not include a model to handle textured paper and other supplementary drawing materials. Takagi and Fujishiro [14] presented a model for paper microstructure and pigment distribution for colored pencils to be used in digital painting. In the commercial realm, some interactive painting systems such as Fractal Design Painter[1] offer pencil, erasers, and blenders models with some interaction with the paper. Our blender and eraser model improves the approximation of graphite pencil renderings on drawing paper.

1.2 Overview

This paper is organized in three parts. In the first part (sec. 2) we present our pencil and paper model [13]. In the second part we present the blender and eraser model (sec. 3) and describe in detail the processes involved when blenders and erasers interact with lead material and paper and how we modeled them (sec. 4). In the third part of the paper (sec. 5) we show results from our models on different paper textures, various pencil swatches, and on tone rendering methods.

2 Background: graphite pencil and drawing paper models

This section briefly describes our pencil and paper model. Details about the model and the computational aspects of the pencil and paper interaction process can be found in Sousa and Buchanan [13].

Our approach is based on an observational model of how real graphite pencils interact with drawing paper. The goal was to capture the essential physical properties and behaviors observed in order to produce quality pencil marks at interactive rates. Our intention was not to develop a highly physically accurate model, which would result in a computationally expensive simulation. All parameters described are important to achieve good pencil simulation results.

2.1 Pencil hardness and points

Every pencil contains a writing core (or "lead") which is made from a mixture of graphite, wax, and clay. The hardness of the lead depends on the amount of graphite and clay. The more graphite it contains, the softer and thicker it is. Pencil hardness is graded in degrees. Usually nineteen degrees are used ranging from 9H (hardest) to 8B (softest).

Sharpening a pencil in different ways changes the shape of the contact surface between the pencil and the paper. A pencil point is defined by a polygonal shape and pressure distribution coefficients over the point's surface.[2]

2.2 Paper surfaces

Paper textures for pencil work (categorized as smooth, semi-rough, and rough) have a slight roughness ("tooth" or grain) that enables lead material lm (graphite Gt, clay Ct, and wax Wt particles) to adhere to the paper. We model the paper texture as a height field $(0 \leq h \leq 1)$ as reported by Curtis *et al.* [2]. These height fields can be either procedurally generated or digitized from a paper sample. Each paper location (x, y) accumulates lead material $lm_{(x,y)}$. The amount of material depends on the pencils that have crossed the location.

2.3 Pencil and paper interaction

Lead material is left on paper through friction between the lead and the paper. The amount of lead material lm depends on the pencil tip shape, the pressure applied to the pencil, and the pencil hardness (degree). A pencil stroke changes these parameters to achieve different effects. In addition to depositing lead, a pencil stroke may alter the texture of the paper by destroying its grains.

We compute the reflected intensity of lead material $Ir_{(x,y)}$ deposited at a particular paper location (x, y). We assume that graphite particles are black, and clay and wax particles are optically neutral components. The reflected intensity depends on the amount of graphite present at (x, y). The amount of graphite is computed as follows:

$$Ag_{(x,y)} = \frac{Gt_{(x,y)}}{TotalLead} \tag{1}$$

where $Gt_{(x,y)}$ is the total amount of deposited graphite particles and $TotalLead$ is the maximum amount of lead material[3]. The reflected intensity is then given by:

$$Ir_{(x,y)} = 1.0 - Ag_{(x,y)} \tag{2}$$

[1] Even though a number of systems offer "pencil" mode it is difficult to determine what physical model, if any, is being used to simulate the pencil, blenders, and erasers.

[2] Our blender and eraser points are modeled in a similar way (see subsecs. 3.1 and 3.2)

[3] The amount of lead material is measured in lpu (lead particle units) necessary to completely cover the paper's location at (x, y). These units are based on the average lead particle diameter (typically between 2 and 10 micrometers) and on the fact that for a particular paper there is a maximum absorption rate of lead and that this can be changed according to the paper. For example it is possible to do a very fine paper with a lead cover on it. Basically only a little bit of lead gets deposited forming a thin layer. We modeled $TotalLead$ to be around 1000 lpu [13].

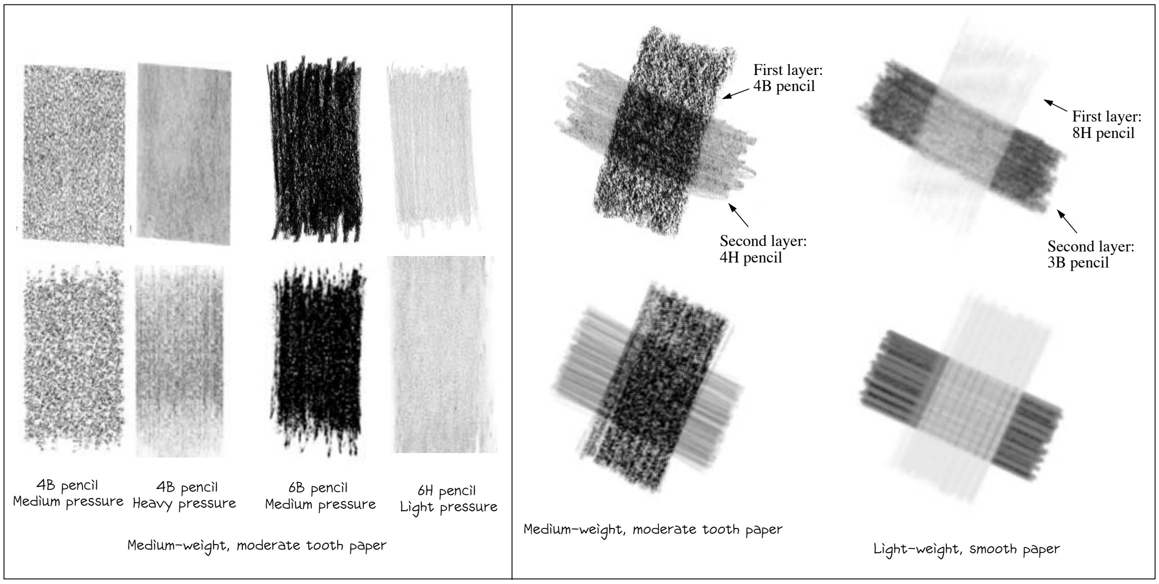


Figure 1: Our pencil and paper simulation model [13] applied over drawing paper (bottom row). Compare results with real pencil work (top row). The set of four swatches made with one single pencil (left box) was generated by adapting our model to an interactive illustration system. The set of blended swatches (right box) was generated by adapting our model to the mark-making primitive [13, 12] which automatically models the variations of a series of parallel pencil strokes to create tones and textures.

Fig. 1 illustrates two sets of results from our pencil and paper model [13].

3 Blender and eraser model

A blender is any tool that can be used to soften edges or to make a smooth transition between tone values. We modeled two kinds of blenders:

1. Tortillon, which is a cylinder made of paper rolled into a long, tapered point at one end for blending tiny areas and fine lines.
2. Stump, which is not as thin and pointy as a tortillon. Made of compressed paper, felt, or chamois, a stump can have up to a half-inch diameter.

Erasers remove surface particles to lighten a drawing. We modeled the kneaded eraser which is one of the most effective erasers made for graphite pencil. It can be used to lighten tones leaving white areas that have been covered, and it does not leave eraser dust behind. Kneaded erasers come in rectangular blocks. A piece of it is cut or torn off and kneaded between thumb and fingers until it becomes soft and pliable. It can be modeled into any shape (Fig. 2).

Like the pencil and paper model [13] our approach is based on an observational model of how real blenders and erasers interact with lead material already deposited on drawing paper. The goal was to capture the essential physical properties and behaviors observed in order to produce quality blenders and erasers marks at interactive rates. Our intention was not to develop a highly physically accurate model which would result in a computationally expensive simulation. All parameters described are important to achieve the blender/eraser simulation results shown here.

3.1 Point shapes

The point shapes for blenders and kneaded erasers are defined as a polygonal outline based on the shape of canonical types of points (Fig. 2). This approach is similar to the modeling of pencil points [13]. A blender/eraser tip is defined as $tip = \{(x_i, y_i), s\}$, $\{1 \leq i \leq n\}$, where (x_i, y_i) are the n vertices of the polygon and s is the scale factor of the polygon used to account for the width of the blender/eraser.

3.2 Pressure distribution coefficients

Pressure distribution coefficients are values between 0 and 1 representing the percentage of the blender's and eraser's point surface that, on average, makes contact with the paper. This value is used to locally scale the pressure being applied to the blender/eraser. We modeled these coefficients in the same way as for pencil points [13]. The pressure distribution coefficients are defined as $pdc = \{(mpdc, x_{mpdc}, y_{mpdc}), (vpdc_i)\}$, $\{1 \leq$

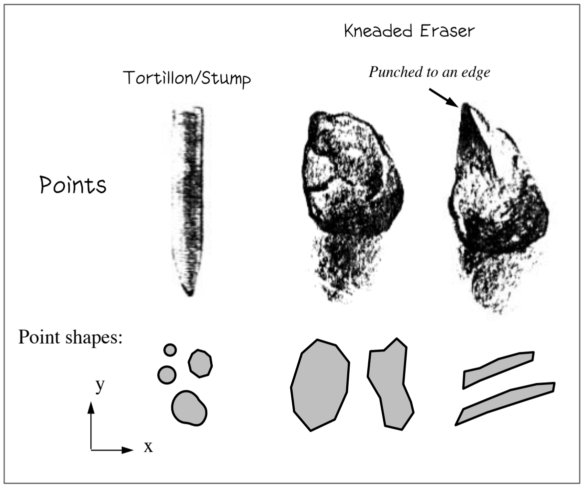


Figure 2: Different kinds of canonical points for blenders/erasers and their polygonal shapes modeling the surface area in contact with the paper.

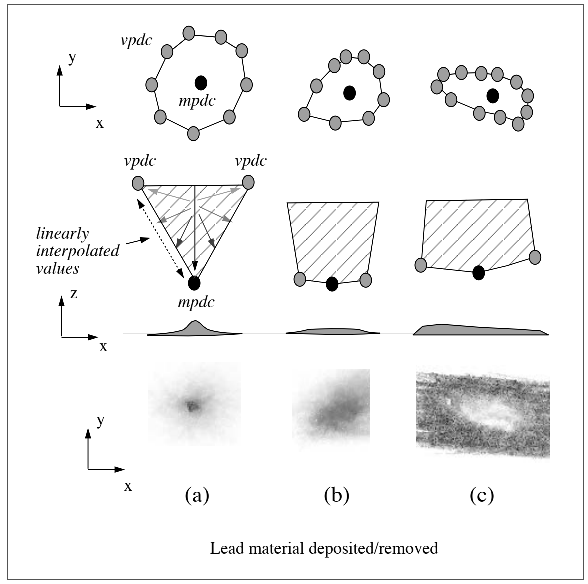


Figure 3: Examples of the xy polygonal shape, cross-sectional views, and results using our model for (a) tortillon and (b) stump blenders, and (c) kneaded eraser. Different values of pressure distribution coefficients ($mpdc$ and $vpdc_i$) across the polygonal shape result in different deposit and removal of lead material over the paper's surface. The results for lead material blended are for $mpdc = 1.0$ and the same $vpdc_i$ value for all vertices in the polygonal shape ((a) 0.2 for the tortillon, (b) 0.5 for the stump). The result for lead material erased (c) has $mpdc = 1.0$ and $vpdc_i$ values with slight variations between 0.7 and 0.9.

$i \leq n\}$ where $mpdc$ is the value of the main pressure distribution coefficient whose location (x_{mpdc}, y_{mpdc}) can be anywhere within the blender's and eraser's point, and $vpdc_i$ is the value of the pressure distribution coefficient at vertex (x_i, y_i) from the polygonal tip shape. Different values can be assigned to $mpdc$ and to each $vpdc_i$. The closer they are to 1.0, the more surface is in contact with the paper. The closer they are to 0.0, the less surface is in contact with the paper. The values of the pressure distribution coefficients between $mpdc$ and $vpdc_i$ are computed by linear interpolation (subsec. 4.3), thus defining the overall shape of the blender's and eraser's point (Fig. 3).

4 Blender and erasers interacting with lead and paper

By flattening out a kneaded eraser, placing it firmly over an area, and then pulling quickly, lead material will be lifted away without rubbing the paper surface. As the kneaded eraser rubs the paper's surface lead material is removed sticking completely to the eraser's point. No lead material is deposited back on the paper.

We modeled this interaction process in three main steps:

1. Evaluate the polygonal shape of the eraser's point (subsecs. 4.1 and 4.2).
2. Distribute pressure applied to the eraser across its point (subsec. 4.3).
3. Process the removal of lead material (subsec. 4.4).

Blending changes the texture of an image. When a graphite pencil is drawn across a surface, it leaves particles on top of the paper fibers. The empty valleys result in a textured look to a line or an area of tone. Blending pushes the lead into the surface so that the paper's low grains become filled. This results in tones that seem smoother, more intense, and deeper in value. As the blender rubs the paper's surface, lead material is removed sticking to the blender's point, and a certain amount of lead material is then deposited back on the paper. The third step for blenders involves both the removal and the deposit of lead material.

The interaction process for each step for blenders and kneaded erasers are explained next.

4.1 Polygonal shape evaluation

The canonical polygonal shape for any selected blender's and eraser's point (Fig. 2) is scaled according to the pressure applied over it. Next the point shape is rotated

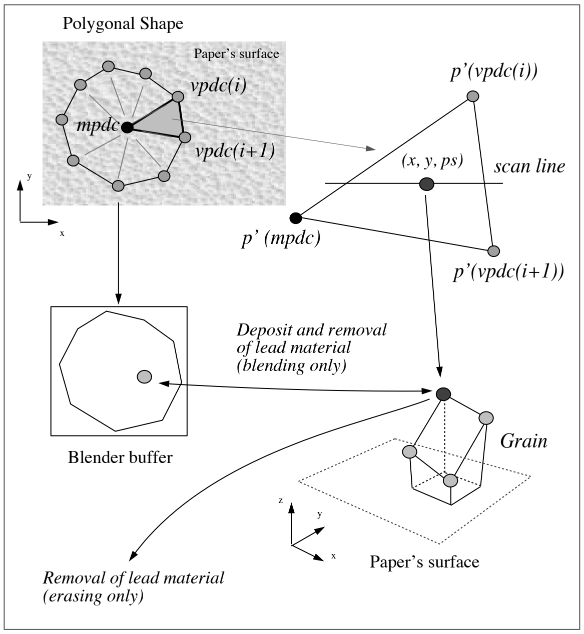


Figure 4: The pressure distribution process across the polygonal shape from the blender's and eraser's point.

by β degrees based on the movements of the wrist and the whole arm. Finally pressure distribution coefficients (subsec. 3.2) are assigned to the scaled polygonal shape.

4.2 Blender buffer

Every blender has a buffer associated with it. This buffer keeps track of the current amount of lead material deposited and removed due to interaction with the paper (subsec. 4.4). Kneaded erasers do not need this buffer because they only remove lead. The buffer is defined as an array of pixels with the same resolution as of the current evaluated polygonal shape defining the blender (Fig. 4). At each location (xb, yb) on the buffer we store and remove lead material $lm_{(xb,yb)}$. For the first polygonal shape every buffer location (xb, yb) is initialized to 0. If the polygonal shape changes then only the size of the buffer is adjusted, preserving the information about lead material that has already been deposited and removed.

4.3 Pressure distribution

The pressure value applied to the blender/eraser p $(0 \leq p \leq 1)$ is distributed across the polygonal shape defining the blender's and eraser's point. This process takes into account the pressure distribution coefficients of the blender's and eraser's point with the paper's surface (subsec. 3.2). Two steps are necessary (Fig. 4):

1. The pressure values p' at the pressure distribution coefficients are evaluated as:

$$\begin{aligned} p'_{mpdc} &= p \times mpdc \\ p'_{vpdc_i} &= p \times vpdc_i \end{aligned} \tag{3}$$

2. The pressure across the polygonal shape is computed by scan converting one line at a time for each triangle from the polygonal shape, resulting in the location (x, y) with the correspondent pressure value ps.

4.4 Deposit and removal of lead material

The transfer of lead material from paper to blender and from blender to paper is computed as follows:

From paper to blender

1. A certain amount of lead material lmr is removed from paper (x, y):

$$lmr \leftarrow lm_{(x,y)} \times (ps \times plr), plr = 0.7, \tag{4}$$

where plr is the percentage of lead material removed.

2. The amount of lead material on the paper is reduced:

$$lm_{(x,y)} \leftarrow lm_{(x,y)} - lmr \tag{5}$$

3. Lead material lmr removed from the paper is deposited on the blender buffer (xb, yb):

$$lm_{(xb,yb)} \leftarrow lm_{(xb,yb)} + lmr \tag{6}$$

From blender to paper

1. A certain amount of lead material is removed from blender (xb, yb):

$$lmr \leftarrow lm_{(xb,yb)} \times (ps \times plr), plr = 0.5 \tag{7}$$

2. The amount of lead material on the blender is reduced:

$$lm_{(xb,yb)} \leftarrow lm_{(xb,yb)} - (lmr \times t) \tag{8}$$

where t $(0 \leq t \leq 1)$ models the absorption/storage capacity of lead material in the blender. The closer t is to 0 the greater the absorption/storage capacity of the blender. We defined $t = 0.2$ for tortillons and $t = 0.5$ for stumps.

3. Lead material lmr is deposited on the paper (x, y):

$$lm_{(x,y)} \leftarrow lm_{(x,y)} + lmr \tag{9}$$

We have found that the values for $plr(0.7, 0.5)$ and $t(0.2, 0.5)$ give credible results. They are based on our observations on the absorption and dispersion behavior of blenders and erasers over deposited lead material. For a kneaded eraser only steps 1 and 2 from *paper to blender* are necessary.

5 Results

This section presents results from rubbing different pencils over different paper textures, using our pencil and paper model [13], and the blender and eraser model presented in this paper. All the results were generated on an OCTANE^{TM} Power Desktop[2] and printed at 200 *dpi* on a 600 *dpi* HP LaserJet 5Si MX printer. Real samples were scanned at 150 *dpi* and printed at 150 *dpi*. We adapted our model to an interactive illustration system using digital samples for the paper's texture. The images from the results show that our simulation model produces similar results to the strokes and swatches generated with real pencils, blenders, and erasers. The images were generated using methods for blenders and kneaded erasers recommended by review of pencil literature [1, 16, 6, 9] and contact with artists and illustrators.

The first set of results (Fig. 5) illustrates the effects of blending and erasing pencil swatches over medium-weight, semi-rough paper's surfaces.

The second set of results illustrate results for tone rendering using a method called smudging [9, 6, 8]. Blenders and kneaded eraser are excellent for this rendering method, used for illustrating soft subject matter and shadows. Three rendering stages are necessary:

1. The tone values in the subject are rendered by using one pencil hardness (degree).
2. Certain portions of the drawing are smudged using blenders.
3. A kneaded eraser is then used to lighten the areas where there are highlights.

5.1 Rendering pipeline

We demonstrate several image-based rendering results for smudging using the models presented. We use reference images of one real pencil drawing (Fig. 6, (*sphere*)), four real pen-and-ink illustrations (Figs. 6, (*cup*), 7, 8, and 9), and one photograph (Fig. 10). The intensity values i at each pixel (x, y) on the reference images define the height field h of the paper's surface (subsec. 2.2) where $h_{(x,y)} = i_{(x,y)}$.

Our goal was to create a pencil rendered version for each of the reference images. The rendering pipeline consists of two stages:

1. This first stage is done automatically by our system (part (b) from Figs. 6 to 10).

   For each paper location (x, y) (correspondent to the reference image pixel location (x, y)) the pencil and paper model [13] is evaluated.

   The computational cost of this stage is due mainly to the evaluation of the pencil point from the pencil and paper model [13] at each pixel on the reference image. Total cost = Number of pixels on the image $\times$ Pencil and paper interaction process (subsec. 2.3) evaluated at each pixel on the polygonal shape for the pencil point (Fig. 3). For the results presented in this paper we use the smallest pencil point, which is equal to one pixel. The response time was satisfactory at interactive rates (see figures' captions).

   The intensity $i_{(x,y)}$ is used to adjust the pressure p applied to a single pencil resulting in the correct amount of lead material deposited at paper (x, y). The pressure p applied to the pencil is the only parameter that changes at this stage, and it is given by $p = 1.0 - i_{(x,y)}$. This means that in order to achieve a darker intensity more pressure is required. This approach is based on traditional pencil rendering methods to create tone values [6].

   If the user provides additional pressure pa then the final pressure value p is scaled as $p = p \times pa$. This is the case for Fig. 10 where pencil strokes using our model were interactively defined over the photograph after the automatic evaluation of the pencil and paper model. In this case the only parameter changed was the pressure applied to the pencil.

2. For this stage we adapt the blender and eraser model to an interactive illustration system. The user interactively controls the blenders and the kneaded eraser to compose the final image (part (c) from Figs. 6, 7, 9, 10, and parts (c, d, e) from Fig. 8). The response time was satisfactory at interactive rates (see figures' captions).

   For each paper location (x, y) (correspondent to the reference image pixel location (x, y)) the blender and eraser model [13] is evaluated, with $mpdc$ (subsec. 3.2) from the blender's and eraser's point (Fig. 4) located at (x, y). The pressure distribution coefficients ($mpdc$ and $vpdc_i$) have values equal to 1.0. For the results presented in this paper we use blender's and eraser's polygonal shapes with resolutions of 1-10 pixels.

   Like in the first stage, the pressure p applied to blenders/erasers is also adjusted according to $i_{(x,y)}$. In this case $pi_{(x,y)} = i_{(x,y)}$, this means that in order to achieve a lighter intensity more pressure is required.

6 Conclusions and future work

We have presented an observational model of blenders and kneaded eraser to be used with the graphite pen-

[2] All rendering is done in software.

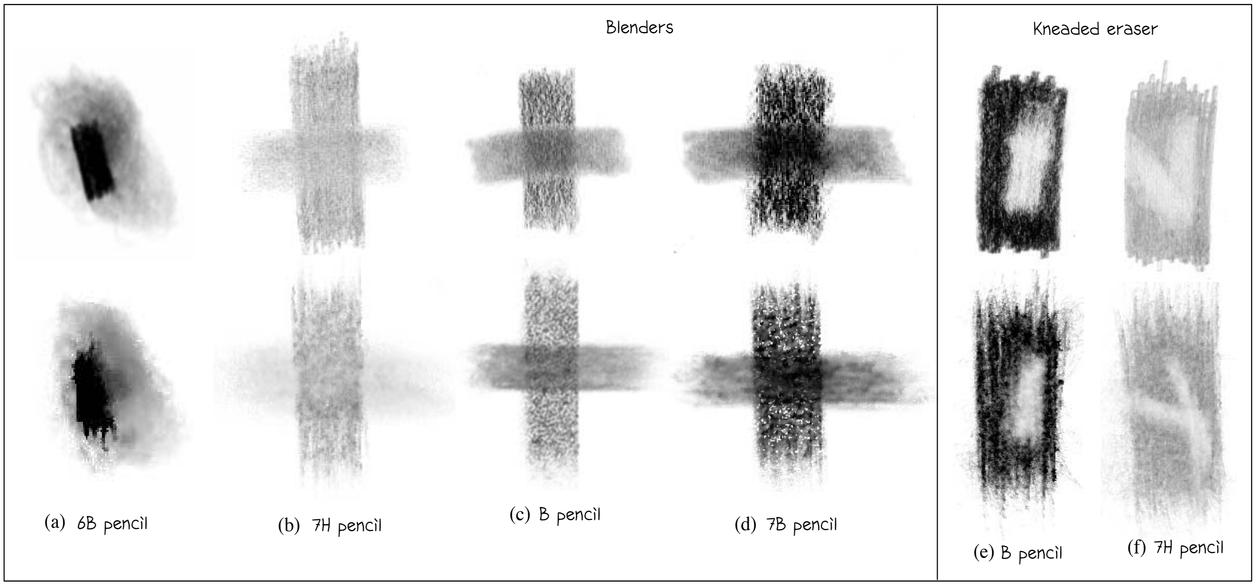


Figure 5: The bottom row shows results from our blender and kneaded eraser model applied over the pencil and paper model [13]. Compare results with real pencil work (top row). For blenders: (a) a 6B pencil was rubbed firmly and then a tortillon was rubbed over it with circular gestures and medium to low pressure (20 secs); (b), (c), and (d): pencil strokes were rubbed vertically and then stumps were rubbed horizontally (15-25 secs).

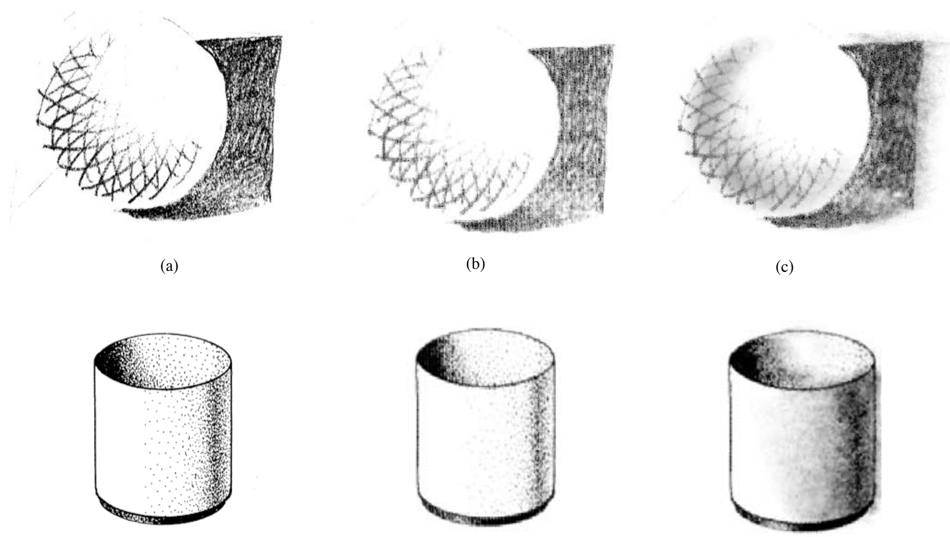


Figure 6: (a) Real pencil drawing of a sphere (resolution of 283x218 pixels) rendered using a very soft pencil and cross-hatching to convey tone values (top row); cup rendered in pen-and-ink (resolution of 240x282 pixels) using ink dots (bottom row). Next stages using our simulation models: (b) Automatic rendering using 2B pencil (1.24 secs for the sphere and 1.36 secs for the cup). (c) Smudging the cross-hatched lines on the sphere (30 secs) and the ink dots on the cup (25 secs) creating a better effect on the tone. Shadow is also smudged around the sphere to make it softer. Notice the excess of graphite which spreads as we smudge the drawing. Kneaded eraser enhances highlight and clear some portions of the shadows (8 secs for the sphere and 10 secs for the cup)

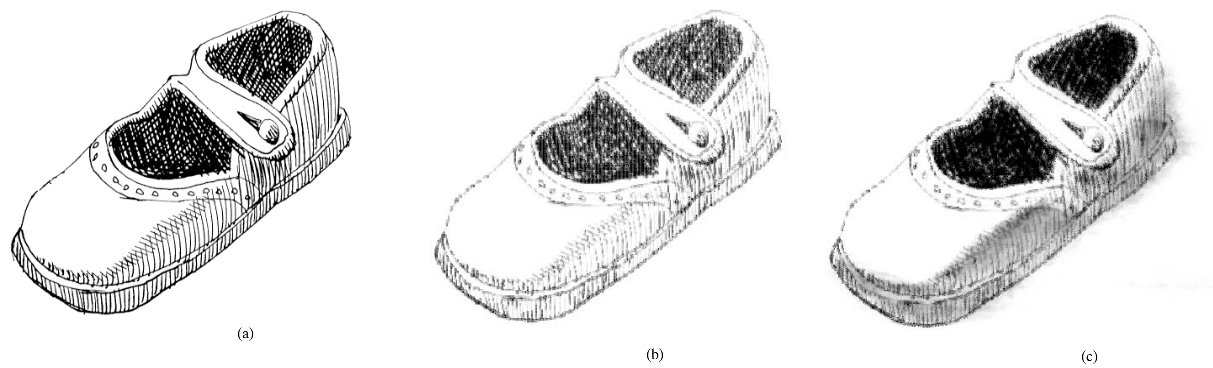


Figure 7: (a) Real pen-and-ink illustration of a shoe (resolution of 402x345 pixels) rendered using a few simple tones that create the illusion of form and depth. (b) Automatic rendering using 3B pencil (2.79 secs). (c) Smudging the lines (30 secs) and then applying the kneaded eraser on top and inside the shoe enhancing its tonal contrast (12 secs).

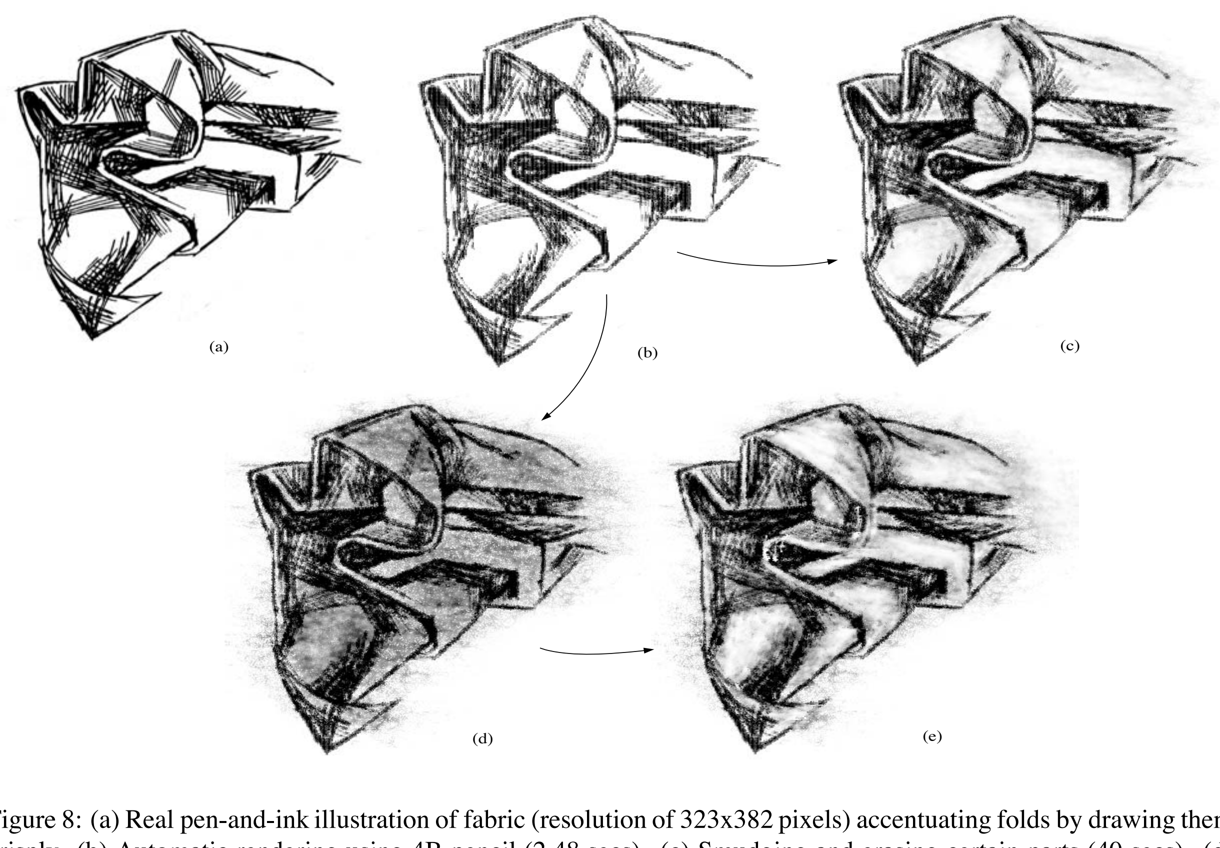
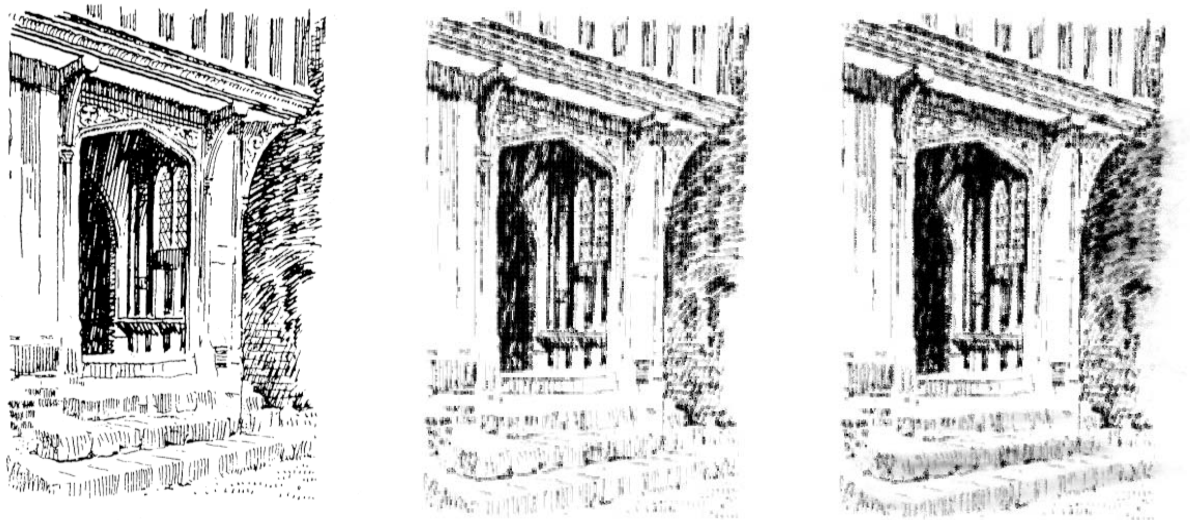


Figure 8: (a) Real pen-and-ink illustration of fabric (resolution of 323x382 pixels) accentuating folds by drawing them crisply. (b) Automatic rendering using 4B pencil (2.48 secs). (c) Smudging and erasing certain parts (40 secs). (d) Smudging the entire drawing from (b) in a relatively flat-tone (30 secs) and then (e) using the kneaded eraser to set up areas of highlights (25 secs) [9, 8].



(a) (b) (c)

Figure 9: (a) Real pen-and-ink rendering on tracing paper (resolution of 320x408 pixels). (b) Automatic rendering using 6B pencil (2.63 secs). (c) Smudging most of the shadow lines and the tone strokes for the bushes (35 secs).

(a) (b) (c)

Figure 10: (a) High contrast photograph of Patricia (resolution of 279x388 pixels). (b) Automatic rendering using 6H pencil (2.18 secs) (first stage, subsec. 5.1) followed by interactive rendering (pencil point from the pencil and paper model adapted to an interactive illustration system) with strokes interactively applied using medium-soft pencils applied with light pressure (15 secs). (c) Smudging the darker tones, the background plane of the photograph, and lightly smudging the shadows and some of the face lines (40 secs). Kneaded eraser lightly applied to emphasize the highlights (30 secs).

cil and drawing paper model presented in Sousa and Buchanan [13]. The model for interaction between blenders and erasers with lead and paper took into account parameters such as the particle composition of the lead over the paper, the texture of the paper, the position and shape of the blender and eraser, and the pressure applied to them. We have illustrated the results of our blender and eraser model by duplicating pencil swatches and by generating images. The images were generated using methods for blenders and kneaded erasers recommended by review of pencil literature and contact with artists and illustrators. The images were generated online in two steps using reference images as input. In the fist step the pencil and paper model is automatically evaluated. In the second step the user specify the tools being used as documented in the figure captions.

Several research issues remain open for future work in computer-generated pencil drawing. We are currently investigating the combination of our pencil model with other simulated media such as watercolor [2] and pen-and-ink [17]. We are also investigating the modeling of higher-level pencil rendering primitives, to automatically render three-dimensional models with a look that emulates real pencil renderings [12].

7 Acknowledgments

This research work was sponsored by the National Council of Scientific and Technological Development of Brazil (CNPq) and by the Natural Sciences and Engineering Council of Canada (NSERC). The authors wish to thank Mark Green, Ben Watson, Paul Ferry, and other members of the University of Alberta graphics lab for their reviews and comments. Further thanks are due to Desmond Rochfort and Barbara Maywood of the Department of Art and Design, University of Alberta for their constructive criticism and positive comments. The authors also thank Paul Lalonde for helping with the translation of the abstract into French and Patricia Rebolo Medici for her reviews, comments, and photograph.

8 References

[1] S.W. Camhy. *Art of the Pencil: A Revolutionary Look at Drawing , Painting, and the Pencil*. Watson-Guptill Publications, 1997. ISBN 0-8230-1373-1.

[2] C.J. Curtis, S.E. Anderson, J.E. Seims, K.W. Fleischer, and D.H. Salesin. Computer-Generated Watercolor. In *Proc. SIGGRAPH '97*, pages 421–430, August 1997.

[3] D. Dooley and M.F. Cohen. Automatic Illustration of 3D Geometric Models: Surfaces. In *Proc. IEEE Visualization '90*, pages 307–314, October 1990.

[4] G. Elber. Line Art Illustrations of Parametric and Implicit Forms. *IEEE Trans. Visualization and Computer Graphics*, 4(1):71–81, January 1998.

[5] P.M. Hall. Non-Photorealistic Shape Cues for Visualization. In *Winter School of Computer Graphics*, February 1995. Univ. of West Bohemia, Plzen, Czech Republic.

[6] D. Lewis. *Pencil Drawing Techniques*. Watson-Guptill Publications Inc., New York, 1984. ISBN 0-8230-3991-9.

[7] L. Markosian, M.A. Kowalski, S.J. Trychin, L.D. Bourdev, D. Goldstein, and J.F. Hughes. Real-Time Nonphotorealistic Rendering. In *Proc. SIGGRAPH '97*, pages 415–420, August 1997.

[8] B. Maywood. Personal communication. *Dept. Art and Design, University of Alberta*, 1998.

[9] G. Price. *Pencil Drawing*. (from the Art is... Video Series). Crystal Productions, August 1993. SBN 1-56290-077-3.

[10] M.P. Salisbury, S.E. Anderson, R. Barzel, and D.H. Salesin. Interactive Pen-and-Ink Illustration. In *Proc. SIGGRAPH '94*, pages 101–108, July 1994.

[11] D. Small. Simulating Watercolor by Modeling Diffusion, Pigment, and Paper Fibers. In *Proc. SPIE, Image Handling and Reproduction Systems Integration*, volume 1460, pages 140–146, August 1991.

[12] M.C. Sousa and J.W. Buchanan. Computer-Generated Graphite Pencil Rendering of 3D Polygonal Models. *Submitted for publication*.

[13] M.C. Sousa and J.W. Buchanan. Observational Models of Graphite Pencil and Drawing Paper for Non-Photorealistic Rendering. *Submitted for publication. Detailed description of the pencil and paper simulation model currently available at the URL http://www.cs.ualberta.ca/∼mario/TR/pencil.ps*.

[14] S. Takagi and I. Fujishiro. Microscopic Structural Modeling of Colored Pencil Drawings. In *SIGGRAPH '97 Visual Proc.*, page 187, August 1997.

[15] A.H. Vermeulen and P.P. Tanner. Pencilsketch — A Pencil-Based Paint System. In *Proc. Graphics Interface '89*, pages 138–143, June 1989.

[16] E. W. Watson. *Course in Pencil Sketching, Four Books in One*. Van Nostrand Reinhold Company, New York, 1978. ISBN 0-442-29230-9.

[17] G. Winkenbach and D.H. Salesin. Computer-Generated Pen-and-Ink Illustration. In *Proc. SIGGRAPH '94*, pages 91–100, July 1994.