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Automatically mimicking unique hand-drawn pencil lines

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A B S T R A C T

In applications such as architecture, early design sketches containing accurate line drawings often mislead the target audience. Approximate human-drawn sketches are typically accepted as a better way of demonstrating fundamental design concepts. To this end we have designed an algorithm that creates lines that perceptually resemble human-drawn lines. Our algorithm works directly with input point data and a physically based mathematical model of human arm movement. Our algorithm generates unique lines of arbitrary length given the end points of a line, without relying on a database of human-drawn lines. We found that an observational analysis obtained through various user studies of human lines made a bigger impact on the algorithm than a statistical analysis. Additional studies have shown that the algorithm produces lines that are perceptually indistinguishable from that of a hand-drawn straight pencil line. A further expansion to the system resulted in mimicked dashed lines.

1. Introduction

Non-photorealistically rendered images can convey information more effectively by omitting extraneous detail (abstraction), by focusing the viewer's attention on relevant features (emphasis), and by clarifying, simplifying, and disambiguating shape [14,35]. In fact, a distinguishing feature of non-photorealistic rendering (NPR) is the concept of controlling and displaying detail in an image to enhance communication. The control of image detail is often combined with stylization to evoke the perception of complexity in an image without its explicit representation. NPR imagery, therefore, allows:

- *the communication of uncertainty*: precisely rendered computer graphics imply an exactness and perfection that may overstate the fidelity of a simulation or representation; and
- *the communication of abstract ideas*: simple line drawings, like the force diagrams used in physics textbooks, can communicate abstract ideas in ways that a photograph cannot.

Although there are many current computer-generated drawing techniques that enable the creation of complex stylized images, such stylization techniques are typically limited to a library of previously drawn strokes and may not provide lines with the qualities of expressiveness and aesthetics that match hand-drawn illustrations.

The ultimate goal of this research is to capture the essence of a single stroke, drawn by humans as straight pencil lines of arbitrary length, and encode it into an algorithm. In turn, an application may use this algorithm to produce a line that resembles a human-drawn line, and it could be used to replace traditional computer-drawn lines (e.g., Bresenham's line algorithm [4]).

A challenge in our work is that no precise metric has been developed to generally differentiate between hand-drawn and computer-generated line drawings, although some attempts have been made for specific techniques, such as stippling [21]. However, humans can typically distinguish differences of these results with relative ease [16]. For pencil lines this may be due to changes in grey levels, a variation not proportional to the path, or a glitch in the path orientation. Such variations make it difficult to produce aesthetically pleasing, natural looking results that mimic human-drawn lines.

We divide our algorithm for generating a human-like pencil lines into two parts: (a) synthesizing the path that corresponds to human arm movement and (b) synthesizing the pencil texture applied along the path [15,28,35], inspired by the textures produced by real pencils. Based on this general approach, our algorithm produces high quality simulations of hand-drawn lines,

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easily incorporated into existing applications, produces lines of arbitrary length and multiple styles, does not require a library of sample lines or user specified attributes (as is the case with [34] technique); it uses only a grey level dynamic range array and a co-occurrence (CC) matrix.

The evaluation of our technique was done by conducting user studies to show that the proposed approach successfully captures and synthesizes aesthetically pleasing lines that mimic hand-drawn lines.

Our contribution, therefore, is a high quality pencil media line reproduction agent for creating aesthetically pleasing lines that mimic human-drawn lines. For this purpose, we use methods of image synthesis and a model of human arm movement for its replication. Our method avoids computationally expensive techniques and large storage space while continuously producing new, unique lines. In addition, the algorithm does not require the setting of user-determined parameters (patterns of deformation, pressure, density, etc.) except for a pencil type selection through the user interface.

A first version of this technique was published in the Computational Aesthetics Conference 2008 [23]. Building on this initial work, more extensive research has been done to analyze and compare real and generated line textures followed by an enhanced explanation of the evaluation strategy. Details involving the original experimental user studies have been added in addition to two algorithms for higher resolution textures and dashed lines.

2. Previous work

Our work draws from research on interactive non-photorealistic rendering methods that approximate artistic hand-drawn images or paintings. We classify this research into three categories: (1) research in human line drawing algorithms that use different style capturing techniques to achieve a replication of a similar stroke containing all of its feature characteristics, (2) texture synthesis methods used in research to reconstruct synthesized images from data taken from natural scenes, and (3) mathematical models replicating unconstrained point-to-point human arm movement trajectories. We review previous work in these three areas in the following.

2.1. Simulating human line drawings

Characteristics of lines in sketched and hand-drawn images have been studied closely in the field of NPR (e.g., [6,16]). Many algorithms captured style characteristics and applied multiple parameters (such as length, width, and pressure). Previous methods [15,28,35] used such style parameters, applied a vector or texture representation of the style to a path, and distorted the piecewise polynomial curve or polygon path to create a stylized line. Other approaches reproduced and synthesized similar styles from example lines [5,9,11,17,19,32].

Our work is inspired by methods that simulate wax crayons (e.g., [26]) and pencils as a medium. Specifically the work by Sousa and Buchanan [33,34] is related to our own, who simulated graphite pencils on a paper medium using a two-level system based on microscopic observations [33]. Their work focused on generating fill strokes, using it for hatching purposes to reproduce artistic drawings. Our method differs because our lines are not restricted to short strokes and can vary greatly in length with no repeating segments. We also base our work on interactive pen-and-ink illustration by Salisbury et al. [27] who described a level-of-detail system that interactively produces multiples of strokes to avoid tediously placing them manually. Our algorithm for drawing lines could easily be incorporated into the above approaches, adding the benefit of a model of human arm movement and a simple perceptual simulation model for graphite pencils without the requirement of a library of lines to copy, paste, and reshape.

Our method differs from the example-based methods explained above in that we do not require example lines to generate unique paths and textures. For each pencil type there exists two pieces of information in the algorithm, a dynamic range, and a co-occurrence matrix. We simply only require vector endpoints to produce lines. Our aim is not to generate varying style from a single given style as seen in example-based methods, but to develop an algorithm that generates lines that vary in path orientation and texture synthesis, mimicking human movement and graphite pencil deposits observed from real straight line drawings on paper.

2.2. Texture synthesis

We were also influenced by a texture synthesis method based upon sequential synthesis [12] that creates a new texture by preserving the second-order statistics of the natural texture into the newly synthesized texture. Gagalowicz and Ma [12] also provided experimental results demonstrating that the visual system is only sensitive to second-order spatial averages of a given texture field, which is one of the reasons we adopted such a methodology. More recent texture synthesis research renames second-order statistics (spatial averages) [12] using the term co-occurrence models or grey level co-occurrence (GLC) models [8]. These are defined as the proportion of second-order probability statistics of pairs of grey levels when their locations differ by a delta in the texture field plane. Copeland et al. [8] used a texture similarity metric based on the texture field of a model texture. The multi-resolution version of their algorithm "spin flip" demonstrated satisfactory performance and resulted in pleasing outputs.

Zalesny and Gool's work [38] also introduced a texture synthesis method based on image intensity statistics by collecting first-order statistics, measured using an intensity histogram, and then extracting the co-occurrence matrix by sampling with point pairs defining a vector. The CCM stores the distribution of intensity differences between the pair of pixels for a given orientation of the vector. The conventional way of calculating the CCM is by summing all the joint probabilities of intensities for a given pixel neighbourhood into their relative position in the CCM. Zalesny and Gool [38] pointed out that the results are better for textures that contain considerable variations, but at some computation cost. In our work we found that the conventional method to acquire the co-occurrence matrix gave adequate results and there was no advantage to be gained using this technique since the textures we use are not so complex.

2.3. Mathematical models of human arm movement

In order to produce a good simulation of a human line drawing, we also examined studies of the coordination of voluntary human arm movements. Human motor production has been analyzed, modelled and documented for well over a century [1,2,29,37]. Over the past few decades, theories of the functions of the central nervous system (CNS) with respect to human arm movement lead to the hypothesis of various mathematical models [3,7,10,20,22,36]. According to these CNS theories, arm movements are produced in either one of two ways: (1) natural movements maintain a constant ratio of angular velocities of joints to bring reduction in control complexity and constrain the degrees of freedom; or (2) hand trajectories are in extra-corporal space, joint