

Digital Tape Drawing

Ravin Balakrishnan^{1,2}, George Fitzmaurice¹, Gordon Kurtenbach¹, William Buxton¹

¹Alias|wavefront
210 King Street East
Toronto, Ontario
Canada M5A 1J7

{ravin | gf | gordo | buxton}@aw.sgi.com

²Dept. of Computer Science
University of Toronto
Toronto, Ontario
Canada M5S 3G4
ravin@dgp.toronto.edu

ABSTRACT

Tape drawing is the art of creating sketches on large scale upright surfaces using black photographic tape. Typically used in the automotive industry, it is an important part of the automotive design process that is currently not computerized. We analyze and describe the unique aspects of tape drawing, and use this knowledge to design and implement a digital tape drawing system. Our system retains the fundamental interaction and visual affordances of the traditional media while leveraging the power of the digital media. Aside from the practical aspect of our work, the interaction techniques developed have interesting implications for current theories of human bimanual interaction.

Keywords

Tape drawing, two-handed input, automotive design, interaction techniques, large-scale displays.

INTRODUCTION

Designers in the automobile industry have traditionally created concept sketches of cars on large scale upright surfaces (walls) that preserve a 1-1 or “full-size” scale factor between the sketch and the final physical car. The main reason for these full-size upright sketches is that designers and managers want to determine and evaluate the principle curves of a design as early in the design process as possible. Working at 1-1 scale is critical to this, if one wants to avoid the unpleasant “surprises” that might otherwise occur if work were done at a reduced scale or on a conventional CRT, for example. While these measures may seem extreme, it is important to recognize that the product being designed could cost up to \$1billion to bring to market. As such, minimizing unnecessary iterations is of utmost importance.

An interesting aspect of these concept sketches is that they are created not by using pencils and paint, but mainly by laying down black photographic tape that feels like common masking tape on the drawing surface.

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TAPE DRAWING

This style of sketching with photographic tape, called “tape drawing”, is achieved by using everyday skills of unrolling the tape with one hand and sliding the other hand along the tape while fastening it on the surface. Even though the mechanics of this naturally two-handed technique are easily explained, the artwork created by experienced practitioners reflects a level of skill that is on a par with any other artistic medium, as the example in Figure 1 illustrates.

Tape drawing has several fundamental advantages over free-form sketching with a pencil, given the large scale size of the sketches. Firstly, it is difficult to draw, freehand, straight lines and smooth continuous curves at this scale. Physical aids such as rulers and french curves would assist the process, however, they would have to be of similar large scale which unfortunately makes them unwieldy for upright use. Drawing with tape, on the other hand, easily facilitates the generation of perfectly straight lines and, due to the slight elasticity of the tape which allows it to be deformed, smooth continuous curves as well. The freehand nature of the interaction is maintained, and yet the tape’s affordances help regulate the user’s actions to allow for creation of smooth continuous lines. In addition, tape drawing has the benefit of easily undoing actions and editing compared to drawing

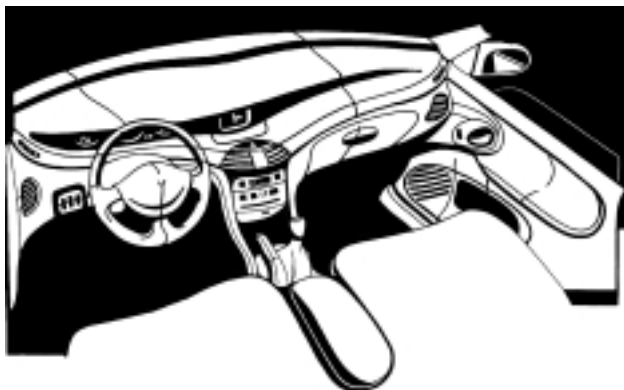


Figure 1. Tape drawing of a car interior using traditional physical tape drawing techniques. This is an extreme example of tape art, illustrating the artist’s skill in the medium. Picture courtesy of Renault Automotive Corp., France.

with pencils or markers. Undo is achieved simply by lifting the tape off the surface. Editing is performed in two ways: first, by lifting the tape off the surface and relaying it, and second, by tearing off strips of tape and replacing with new tape as required.

While the advantages inherent in drawing with tape have ensured its place in the automotive design process, there are nonetheless several problems with this medium.

Firstly, of all the artists working on the initial design, the skill of the tape artist is the farthest removed from traditional computer graphics systems, and yet, the results of their work must eventually be transferred into the computer. While the resolution and fidelity of the tape from both the input and output perspectives are extremely high, there is no easy way to retain this fidelity when transferring the information to electronic formats. Currently, this transfer process is done laboriously by digitizing the key curves of the tape drawing using a hand-held position sensor and then recreating these curves in a CAD package. This transfer process invariably introduces inaccuracies in the electronic version which then have to be identified and removed. Also, since designers create multiple 2D tape drawings which represent different views (such as a front and side view) of the underlying 3D vehicle, these 2D drawings have to be integrated when creating the final 3D model of the vehicle. This integration requires careful alignment and matching of the primary curves of the model, a process that can also introduce errors.

The second major problem with tape drawings is the difficulty in storing and retrieving old drawings. These drawings are typically done on stretched mylar surfaces which when untacked from the wall contract and distort the drawing. Yet, this must frequently be done in order to accommodate changes in the engineering drawings that typically underlay the mylar surface on which the tape drawing is done. Once it is taken down, the purity and accuracy of the original

drawing cannot be maintained. Also, the tape itself tends to fall off the mylar surface after a period of time.

Finally, the physical nature of these drawings preclude easy sharing of design information between different design studios.

These disadvantages of physical tape drawing can potentially be alleviated if digital electronic media were used to create the drawing from the start. This would reduce the errors when transferring, retrieving and storing the tape drawings. An electronic system could also provide functionality beyond what is possible using the traditional media. However, given the aversion of most tape artists to current computer modeling software that require them to learn new skills unrelated to their art, we are faced with the challenge of designing an electronic system that will allow them to easily transfer the considerable skills they have acquired in working with the traditional media. Therefore, such a system must retain the desirable simplicity, fluidity, and affordances of the physical tape drawing techniques.

In this paper, we discuss the design and prototype implementation of a digital tape drawing system (Figure 2). We also present preliminary feedback from tape artists at several automotive design studios, and consider their implications for future enhancements to the system. In addition to the practical aspects of this work, the interaction techniques we developed provide some interesting insights into current theoretical models of two-handed interaction.

DIGITAL TAPE TOOL SYSTEM

Design Process

By observations and discussions with designers at automotive design studios, in particular at Renault and the General Motors Design Center, a few members of our team began to identify and isolate the problems inherent with the traditional tape drawing process. In addition to these direct demonstrations and discussions, we obtained from two design

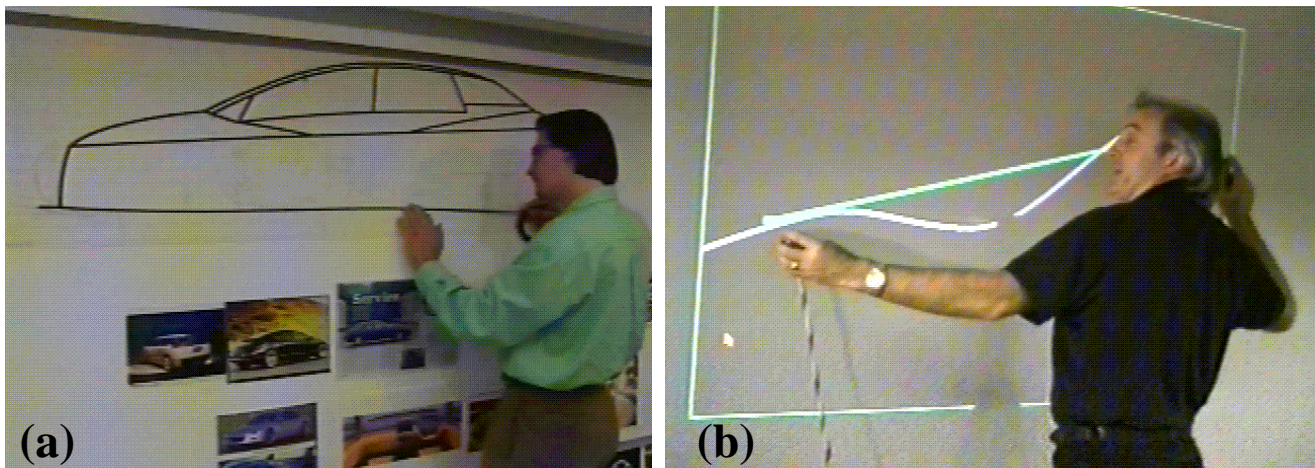


Figure 2. (a) shows an artist drawing with traditional tape techniques. Photo courtesy of General Motors Design Center. (b) shows our digital tape drawing system, and how a user would “sight down a curve”.

studios, at General Motors in Detroit and Renault in France, videotapes of tape artists at work. This served as a reference to guide our work as well as enabled members of our team who had not been to the design studios to get familiar with the tape drawing process. We solicited work from two major studios in order to extract the general practices used in tape drawings and to recognize the idiosyncratic practices used only by a few individual artists. For our prototype, we felt it necessary to begin by supporting the general techniques. Future versions could potentially be tailored to the specific needs of individual artists and studios.

Goals

A primary requirement for our digital tape drawing system was that it be “walk-up and use” for tape artists. Since the goal is to replace traditional tape drawing while enabling tape artists to leverage their current skills, the main functionality of our system had to closely resemble that of traditional tape drawing. Any additional functionality made possible by the digital media would be secondary to the basic ability to place and edit “electronic tape” on a large scale surface.

Prototype Implementation

The variations in physical infrastructure and work practices at different auto studios dictate that any system we eventually deploy for real use has to be tailored to the needs of each studio. Our current implementation is designed to encompass those aspects of the tape drawing process that are common across all studios. Also, in order that we can demonstrate the system and obtain user feedback from various studios, our implementation has to be portable. This introduces some constraints that would not necessarily be present in a fixed installation. The tradeoffs we made are discussed as we describe the system’s components.

Display Surface

Most automotive design studios have a variety of large scale vertical computer display systems, often called “powerwalls”. These powerwall displays use state-of-the-art rear or front projection technology. Very high resolution is achieved by using multiple projectors side-by-side with a slight overlap in images to create a single seamless large image. Image size can range from 8x6 to 50x10 feet. These displays are typically used to display full-size images of car designs during the design and engineering process. Our goal is to leverage off these existing displays not just as an output medium, but also as a surface for digital tape drawings.

Our implementation uses a Hughes/JVC G1000 digital projector with a true 1280x1024 image back-projected onto a collapsible 8x6ft screen. The size of the screen and projector, and the fact that the digital projector requires minimal calibration (unlike older 3-gun RGB projectors), ensures that our system is portable. The 8x6ft screen represents the minimum powerwall size, and is sufficient for us to implement tape drawing interaction techniques that utilize large scale gestures. Similar display sizes have been used in research systems such as Krueger’s VIDEOPLACE [10].

Input Devices

Since tape drawing naturally uses both hands, we need to be

able to sense the position of both hands on the display surface. There are potentially several solutions to this sensing problem. These include optical tracking techniques [3], the use of transparent digitizing tablet on the display surface, touch sensitive transparent display surfaces, and electromagnetic/ultrasonic trackers. Our prototype uses an Ascension Flock-of-Birds six degree-of-freedom electromagnetic tracker held in each hand. Each tracker is augmented with a single momentary switch. We only use two translational degrees-of-freedom (left-right and up-down) of the tracker in our prototype.

Interaction Techniques

Laying Tape

The first requirement of a digital tape drawing system is the ability to lay down digital tape segments on the display/drawing surface. As discussed previously, in order to transition tape artists to this new media, we had to replicate, as closely as possible, the affordances of the physical tape laying process. In the physical media, the right hand unrolls the tape, while the left hand slides along the tape while fastening it to the surface¹. In order to create a continuous smooth line, tension in the tape must be maintained between the two hands. If the right hand is held steady while the left hand fastens, the result is a straight line. The segment of unfastened tape between the two hands can serve as a preview of the line. Curves are obtained by simultaneously moving the right hand in an appropriate arc while fastening with the left hand.

These techniques are preserved in our digital tape laying algorithm. By default, the right hand controls a cursor which represents the roll of tape. The left hand controls a second cursor representing the end of the tape. Both cursors are controlled in a 1-1 manner by the trackers which operate in absolute, linear position control mode. A segment of digital tape, represented as a polyline, always extends between the two cursors. We refer to this as the *unfastened tape segment*. The digital tape is represented as a 1cm thick line on the display. Moving the two hands around effectively moves the unfastened tape segment on the screen. The distance between the two hands determines the length of this unfastened tape segment (Figure 3a).

In order to fasten portions of the digital tape, the left hand presses the button on its tracker (putting it into “fasten mode”). This corresponds to the act of pressing down on the tape in the physical version. Releasing the left hand button cuts the tape currently being laid at the position of the left hand cursor.

1. Note that we use the terms “right” and “left” rather than “dominant” and “nondominant” since all the artists we observed were consistent in their mapping of task to hand, regardless of any underlying handedness. The exact reason for this is not known, although we speculate that it is due to the direction in which these drawings have traditionally been created (starting from the left of the drawing surface and moving to the right)

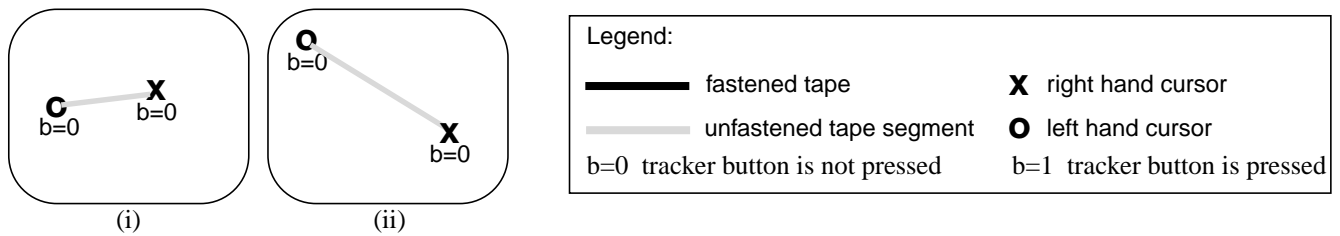


Figure 3a. *Unrolling digital tape.* (i) An unfastened tape segment is always extended between the two cursors when the tracker buttons are not pressed. (ii) The length, position, and orientation of this unfastened tape segment can be changed by moving the cursors.

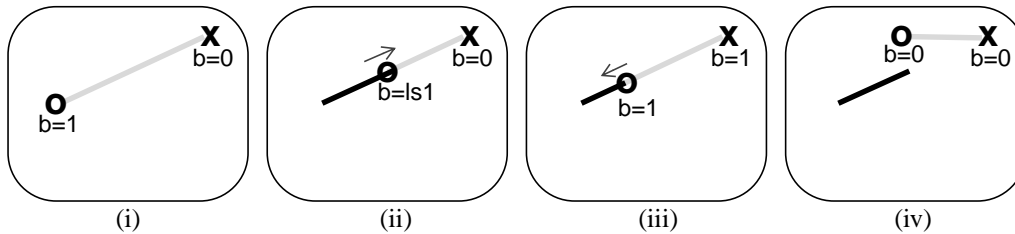


Figure 3b. *Taping straight lines.* (i) To start taping, the left hand tracker button is pressed. (ii) Keeping the right hand in a fixed position, the left hand lays down tape as it slides along the unfastened tape segment between the two cursors. Movement of the left hand cursor is constrained to the unfastened tape segment in the direction towards the right hand cursor. (iii) A tape segment can be unfastened (undo) by pressing the right hand tracker button and backtracking along the previously laid tape with the left hand. (iv) Releasing the left hand tracker button cuts the tape at the location of the left hand cursor and returns the system to the default state shown in Figure 3a.

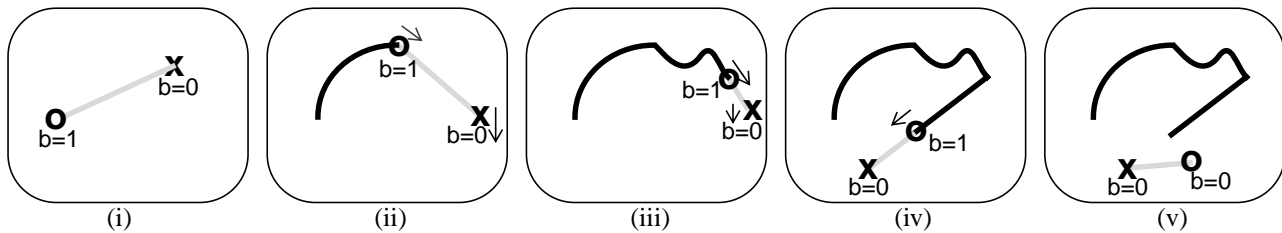


Figure 3c. *Taping curves.* (i) To start taping, the left hand tracker button is pressed. (ii) While moving the right hand, the left hand lays down tape as it slides along the unfastened tape segment between the two cursors. Movement of the left hand cursor is constrained to the unfastened tape segment in the direction towards the right hand cursor. A long unfastened tape segment results in smooth curves with a gradually changing tangent. (iii) Reducing the length of the unfastened tape segment permits the generation of higher variation curves with a more rapidly changing tangent. The length of the unfastened tape segment can be changed on-the-fly simply by moving the two cursors closer or farther apart. (iv) Switching from taping curves to taping straight lines is achieved by simply keeping the right hand cursor in a fixed position while taping with the left hand. An explicit mode switch is not required. (v) Releasing the left hand tracker button cuts the tape.

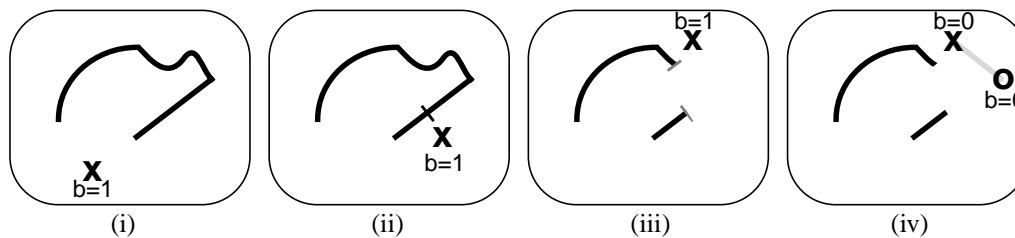


Figure 3d. *Cutting tape.* (i) When not in tape laying mode (i.e., the left hand tracker button is not pressed), pressing the right hand tracker button engages cut mode. The left hand cursor is hidden. (ii) With its button pressed, the right hand cursor makes the first cut point. The button is then released. (iii) When the second cut point is specified (using the same interaction as in step ii), the tape segment between the two cut points is removed. The process in steps ii and iii can be repeated to cut additional tape segments if desired. (iv) Releasing the right hand tracker button completes the cut operation and returns the system to the default mode.

Figure 3. Laying and editing digital tape.

In a manner similar to drawing with physical tape, straight lines are created by holding the right hand steady while the left hand, with tracker button pressed, slides along the unfastened tape segment, fastening the tape as it moves. (Figure 3b). While in the physical version the tape itself serves as a constraint for creating straight lines, our digital version enforces this constraint in software by restricting the left hand cursor to move only along the unfastened digital tape segment, towards the right hand cursor. This ensures that once digitally fastened, the digital tape cannot be unfastened inadvertently (without invoking an edit operation to be described later). If the absolute left hand tracker position strays from the unfastened digital tape segment, its cursor position is determined by a simple projection of tracker position to the nearest point on the unfastened tape segment.

Creating curves in our digital system also mimics the physical equivalent. Unlike the creation of straight lines, both hands must move at the same time. Thus, the unfastened tape segment moves while the left hand fastens the tape (Figure 3c). The length of the unfastened tape segment effectively serves to regulate the smoothness of the resulting curve. Since the left hand cursor is constrained to move along the unfastened tape segment, a longer segment effectively reduces the range of movement of the fastening point controlled by the left hand, resulting in smoother curves (i.e., curve whose tangent changes gradually). A short (approaching zero) unfastened tape segment length reduces the technique to the equivalent of free-hand sketching with the non-dominant hand. An interesting aspect of this technique is that it effectively uses constrained two-handed gestures to control the smoothness of curves. In contrast, most computer tools for generating curves rely on mathematical approaches for specifying smoothness.

From the perspective of two-handed interaction, our digital tape laying techniques are interesting in that they allow for the generation of straight lines and curves without a conventional mode switch. The simple act of moving or not moving the right hand while the digital tape is being fastened determines whether a straight line or curve is generated.

Editing

As with laying down tape, our system's editing operations also emulate the physical process. First is the ability to undo the tape currently being laid down. In the physical media, the artist simply has to pull the tape off the surface. The trackers used in our system could sense a third degree-of-freedom (moving towards/away from the display surface) and thus allow us to duplicate the physical tape undo process. In practice we find that the lack of physical adhesion of the digital tape (we have virtual adhesion) results in users not always operating directly on the display surface, but often float a few inches above the surface. Thus, our undo operation requires that the user explicitly press the button on the right hand tracker. This allows the left hand to pull back on the fastened tape. Since the left hand must be in "fasten mode" (i.e., its tracker button is pressed), it can quickly relay the tape if desired.

The second editing operation is cutting of tape segments (Figure 3d). Similar to cutting physical tape, the digital ver-

sion requires that the user specify two cut points on the tape. This is done by pressing the right hand tracker button, with the left hand tracker button not pressed (i.e., it is not in "fasten mode"), and specifying the two cut points in turn. When the second cut point is specified, the tape segment between the two points is removed. At any time, a partially executed cut operation can be aborted by pressing the left hand tracker button and returning to "fasten mode".

Supporting Operations

In addition to the core operations of laying and editing tape, we also support several additional operations.

Traditional tape artists typically draw on a surface with an underlaid grid. We provide a similar functionality that can be toggled on/off via the keyboard. Also, tape drawings are often made with reference to engineering specifications (called the "engineering package") that delimit the unchangeable dimensions of a car's components. The designer has to work within this engineering framework. In the physical media, this package information is simply printed onto large size paper and attached to the tape drawing surface. We provide this functionality in two ways. First, the system has the ability to import this information which is then displayed as a background image. Second, we can make the background of our tape drawing application window transparent and thus tape drawings can be created on top of any other application window. This allows for drawings to be created right over the application used to create the engineering package.

Finally, we provide the ability to save and load tape drawings to/from files. The file format can be read by other 3D automotive modeling applications such as Alias AutoStudio.

User Feedback

Throughout our development of the digital tape drawing system, we sought user feedback from both our in-house artists and external customers at automotive design studios. A total of three in-house artists were consulted. In addition, due to the portable nature of the system, we were able to demonstrate the prototype to five major auto design studios located in England, France, and the United States. Approximately 20 professional tape artists tried the system for periods ranging from a few minutes up to 30 minutes. The observations we made and feedback we received can be placed in three categories: interaction issues, visuals, and requests for additional features.

Interaction Issues

Perhaps the most important validation was that tape artists were indeed able to walk up and use our system. The only instructions they required were the roles of the two trackers and their buttons (under 1 minute of instruction). Within a minute, traditional tape artists were doing drawings which were clearly superior to that of our system developers who had multiple hours of familiarity with the system. Thus, despite some issues with the tracker and display technology (discussed below), the artists were able to permeate any technological limitations and transfer their skills to the new system, indicating that we had successfully emulated their

traditional interaction techniques. Particularly promising was their use of familiar gestures such as laying a tape segment and looking at it from the side of the screen to inspect the quality of the curve. This inspection technique, called “sighting down the curve” is commonly used in the physical media (see Figure 2a).

Other issues with respect to the interaction were:

- the tracking technology we used suffered from several problems including imprecise calibration, jitter, and encumbrance of the tether wire. We are investigating alternative input technologies, including modified wireless mice that can be used on an upright surface.
- initially, the cursors were displayed directly beneath the absolute tracker position. This resulted in the user’s hand obscuring the cursor. Our solution was to offset the cursors by a fixed distance from the hand/tracker. This offset did not cause the users any difficulty when operating the system.
- a few users commented on the loss of physical tension between the two hands that is afforded by physical tape. We experimented with retractable tapes and elastic bands to simulate this tension, but found that this unnecessarily encumbered the user without much added benefit. It is noteworthy that when mimicing traditional techniques, one should be cognizant of the different affordances of electronic media and avoid trying to duplicate all physical properties without considering possible alternatives (in this case, visual tension seems to suffice).
- users sometimes found it difficult to join tape segment ends accurately. This can be solved by improving the precision of the tracking technology, or taking advantage of the electronic media and introducing virtual features like smart snapping of endpoints when desired.
- in traditional tape drawing, tapes of various widths are used to create various effects. The ability to change the width of the digital tape interactively would provide this functionality. Also, special effects such as tapering the ends of a curve could be provided in the software.
- a property of physical tape is that the wider the tape, the harder it is to bend smoothly. Some users requested that a similar feature be available in the digital version.
- when editing a curve, designers often lay a new curve tape immediately above or below the curve they wish to edit, using the old curve as a guide. They then remove the old curve. This allows them to iteratively refine the shape of the curve. In the digital system, users have suggested that when a new curve is drawn over or close to an existing curve, the older curve should be displayed “greyed out”. A potential problem is determining when the user intends to iteratively modify a curve shape versus simply laying down a new curve.

Visuals

As we expected, users voiced several concerns with respect to the visual aspects of our system:

- the resolution of the large screen display, while acceptable when viewed from a distance, is considerably degraded when viewed up close. Unfortunately, this is a

limitation that can only be solved as display technology improves. One interim solution is to print the tape drawings and mount them on a wall. This would allow the artist to use the beneficial aspects of the digital media, while providing a high quality display for review purposes.

- while many design studios have existing powerwalls, some are in the planning stage and were concerned with the space needed to rear-project a display. Possible solutions are to use mirrors to compact the optic path as well as hang projectors from the ceiling. Also, some managers wanted to consider using a portable system which could be moved between design studios when needed.
- while it is possible to “sight down a curve” in our digital tape drawing system, a few artists made the observation that their traditional physical tape boards have a slight convex curvature to facilitate this inspection operation. A similar configuration with the projection screen is possible.
- finally, artists suggested being able to display additional artwork images (concept artwork, renderings, target audience) along with the tape drawing to support the design process as well as for formal design reviews.

Feature requests

A number of enhancements and new features were suggested by the tape designers:

- beyond the tape drawing abilities, designers wanted access to sophisticated painting facilities which would allow for even more advanced rendering effects such as air-brushing along the edges of curves, to create stylized renderings as shown in Figure 4.
- some of the more computer savvy designers wanted us to develop more sophisticated interaction techniques that go beyond mimicing traditional tape operations and properties. While this may go against our design principle of “keeping things simple”, there are opportunities for more advanced features. For example, some curve editing tools found in desktop applications such as tangency manipulators could be adapted to work on the powerwall.
- to compare two tape drawings, a common drawing scale was proposed. This will allow two or more tape drawings to be superimposed and compared as well as facilitate reusing portions of the drawings.
- designers requested that we integrate the tape drawing system with existing curve and surface evaluation computer packages.
- the digital tape drawing package could be extended to offer traditional drawing tools such as circles and rectangles which would be a time saving. Importing clip art and images (e.g., wheels, hub caps, interior console components like vents, stereo controls, basic materials like leather, vinyl, etc.) to augment the tape was also deemed important.
- with improved tracker accuracy, designers suggested a simple “ruler” mode that would measure the distance between the two trackers in the current tape drawing scale. This would enable them to create accurately scaled drawings.

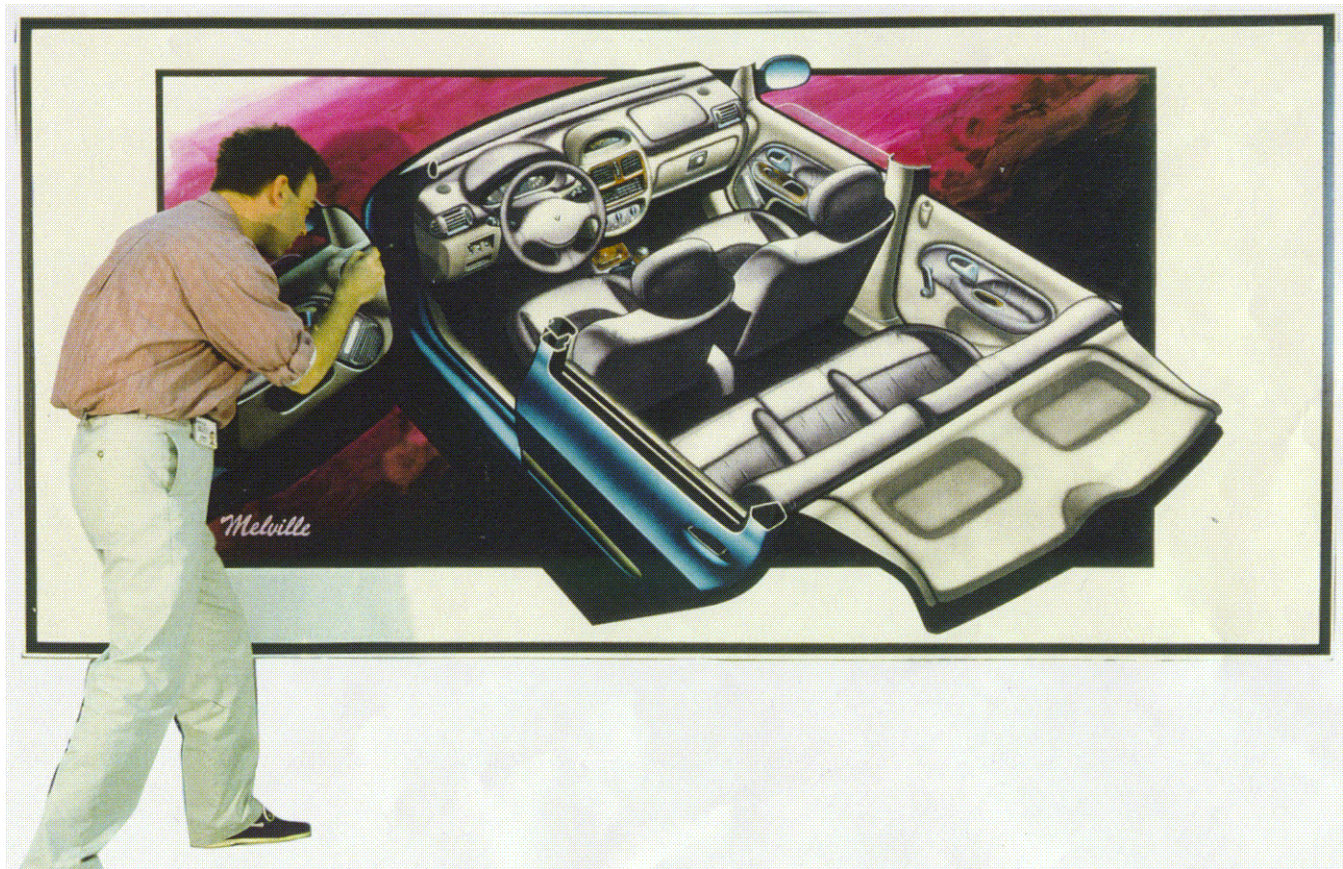


Figure 4. Tape artist working on a tape drawing to which sophisticated paint effects have been added. Photo courtesy of Ken Melville, Renault Automotive Corp., France.

- a flood “fill region” feature was requested as this is often quite laborious using strips of physical tape.
- one designer suggested implementing a symmetry drawing mode which would lay down duplicate mirror-based curves given a predetermined input plane. This is motivated by the fact that many components in a car have symmetrical counterparts (e.g., two headlights).
- some designers suggested a new workflow which enabled them to load a 3D model from a CAD package and select the “defining curves” to be transformed and exported to the digital tape drawing system. Here the defining curves could be edited, reviewed and then imported back to the CAD package to have the rest of the model update given the new curve shapes.

IMPLICATIONS FOR TWO-HANDED INTERACTION

In designing our digital tape drawing system, we attempted to mimic, where appropriate, the interactions used in traditional physical tape drawing. As a result, the interaction techniques developed for our system are founded in established practise rather than theory. However, these practical techniques provide some valuable insights into a currently established theory of two-handed interaction.

Much recent work in bimanual user interfaces [1, 2, 5, 6, 7, 9, 11, 12, 13] has been guided by the theoretical work of Guiard [4]. In his Kinematic Chain (KC) model of skilled

bimanual action, the two hands are thought to be two abstract motors assembled in a serial linkage, thus forming a cooperative kinematic chain. Three general principles emerge from this model:

1. *Dominant-to-Non-Dominant Spatial Reference:* The non-dominant hand sets the frame of reference relative to which the dominant hand performs its motions.
2. *Asymmetric Scales of Motion:* The two hands operate in asymmetric spatial-temporal scales of motion. For instance, when writing on a piece of paper, the motion of the non-dominant hand controlling the position of the paper is of lower temporal and spatial frequency than the writing movements of the dominant hand which nonetheless depends on the non-dominant hand’s movement for spatial reference.
3. *Precedence of the Non-Dominant Hand:* Contribution of the non-dominant hand to a cooperative bimanual task starts earlier than the dominant hand. In the handwriting example, the dominant hand starts writing *after* the paper has been oriented and positioned by the non-dominant hand.

This model has been explored and largely validated in the virtual manipulation arena by Hinckley [6, 7]. Leganchuk, Zhai, and Buxton [12] also used this model to help reason about the manual and cognitive benefits they found in an experimental study on bimanual input.

Now, the primary tape laying interaction technique described in this paper is an asymmetrical cooperative task in that each hand plays a different role but in cooperation they both lay tape. As such, one would expect that given its successful use over the years by tape artists, this technique would conform to Guiard's principles of asymmetric bimanual action.

In the tape laying technique, however, the frame of reference is set by the *right* hand which controls whether the tape is laid as a straight line or a curve, as well as constraints the movement of the *left* hand. Thus, for right-handed artists, it does not conform to Guiard's principle #1. Recall that *all* the artists we observed used their right hand in this manner, regardless of whether or not they were inherently left or right handed. Thus, for left-handers, their nondominant (right) hand would be setting the frame of reference, conforming to principle #1.

When we consider the scales of motion of the two hands in the tape laying technique, they do indeed operate at different spatial and temporal scales. In contrast with Guiard's principle #2, however, for right handers the *nondominant left* hand operates at a higher spatial frequency since it does the precise task of determining exactly where and when to fasten the tape. Again, since left-handers would use their *dominant left* hand for this role, they do not deviate from this principle.

Finally, with respect to precedence of action, if one considers that the *left* hand starts the whole process by specifying the initial fastening point of the tape, then our technique conforms to Guiard's principle #3 (for right-handers, but deviates for left-handers). However, if we move further along the tape laying technique, the left hand's act of fastening the tape *follows* the right hand's act of specifying the constraint. In this case, right-handers would not conform to principle #3 while left-handers would.

These deviations from Guiard's theory, to varying degrees for left and right handers, indicate that more analysis and refinements are required to adequately explain human bimanual interaction. When considering possible explanations, we observe that the tape drawing technique involves a complex interplay between the hands which sometimes switch roles (in terms of precedence) dynamically. Also, for right handers, the tape itself (either physical or virtual) seems to enhance the ability of the nondominant left hand, steadying it and in some sense promoting its role to be equivalent or even superior to the dominant hand. This is particularly evident when the nondominant hand is used to do the precision task of fastening tape. Finally, the fact that both left and right handed artists operated the interface with the same assignment of hands to task, raises the question if the left to right nature of the drawing task is taking precedence over any inherent handedness. These factors should be considered in future refinements of theoretical models of two-handed interaction.

Aside from the theoretical implications, our system also demonstrated a practical design solution for seamless mode switching that could be applied to other two-handed sys-

tems. Based on whether the two cursors are moving simultaneously or in sequential manner, we were able to implicitly switch between two modes (in our case, drawing straight lines or curves). In addition to using the temporal characteristics of the motions of the hands, the relative proximity of the hands could also be used to invoke different functionality. For example, when drawing curves in our system, keeping the hands close together resulted in high variation curves, whereas moving them apart resulted in smooth, gently varying curves. Another possible use of this proximity information is to display (perhaps by gradually fading in) a ToolGlass palette [1] when the hands are close together. This implicit "on demand" interface is similar to that proposed by Hinckley and Sinclair [8] who use implicit touch as a trigger.

CONCLUSIONS and FUTURE WORK

As we have observed during our interactions with artists, designers, and managers at automotive design studios, the process and display of tape drawings serve as a fundamental way to communicate ideas and designs to artists, managers and engineers on an automotive design team.

In order to enhance this communication and facilitate integration with other computer based tools in the design workflow, we developed a novel two handed digital tape drawing system based on traditional tape drawing practices. We believe that our digital tape system preserves the key properties of the physical tape medium while taking advantage of the digital medium. Our approach has focused on respecting the skills of traditional tape artists and have them transfer these skills to the electronic medium. Systems like these hold the potential to ease the transition of artists to adopt computer-based drawing, drafting and evaluation tools in their workflow.

Since tape drawings consist of merely lines and curves, designing a system to enable the creation of these elements at first sight appears to be trivial. However, this is not the case since we need to capture the subtleties afforded by this unique medium. The obvious solution of using a stylus and digitizer to draw lines and curves does not capture these subtleties. In particular, as we have demonstrated, the two-handed technique provides for easy creation of smooth gently varying curves that are difficult to achieve with free-hand sketching. As emphasized in the introduction, working on a one-to-one scale is also important. This requirement precludes the use of standard desktop input technologies. As we have learned, getting the subtleties of the interaction correct are fundamental to providing an easy to use, fluid, and expressive system.

We have plans to extend the digital tape drawing system in a variety of ways. Beyond implementing some of the features suggested by the users, we wish to explore techniques that would extend the system from a primarily 2D drawing system to a 3D drawing system. One 3D approach is to have artists design on a large virtual brick, where they can lay down virtual tape on different brick faces and generate a truly 3D model.

Beyond the design and development of the drawing interac-

tion techniques, we have presented tape drawing as a case study of an asymmetrical two-handed task that highlights some shortcomings of established theory on two-handed interaction.

Through further extensive user feedback and site visits, we are hopeful that the digital tape system continues to evolve and is integrated into the work practices at automotive design studios.

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REFERENCES

- [1] Bier, E. A., Stone, M. C., Pier, K., Buxton, W., & DeRose, T.D. (1993). Toolglass and magic lenses: The see-through interface. *Proceedings of the ACM SIGGRAPH Conference*, 73-80, New York: ACM.
- [2] Cutler, L.D., Frohlich, B., & Hanrahan, P. (1997). Two-handed direct manipulation on the responsive workbench. *Proceedings of the 1997 Symposium on Interactive 3D Graphics*, 107-114, New York: ACM.
- [3] Elrod, S., Bruce, R., Gold, R., Goldberg, D., Halasz, F., Janssen, W., Lee, D., McCall, K., Pedersen, E., Pier, K., Tang, J., & Welch, B. (1992). Liveboard: a large interactive display supporting group meetings, presentations and remote collaboration. *Proceedings of the CHI'92 Conference on Human Factors in Computing Systems*, 599-607, New York: ACM.
- [4] Guiard, Y. (1987). Asymmetric division of labour in human skilled bimanual action: The kinematic chain as a model. *Journal of Motor Behaviour*, 19, 486-517.
- [5] Hinckley, K., Pausch, R., Goble, J.C., & Kassell, N.F. (1994). Passive real-world interface props for neurosurgical visualization. *Proceedings of the CHI'94 Conference on Human Factors in Computing Systems*, 452-458, New York: ACM.
- [6] Hinckley, K., Pausch, R., Proffitt, D., Patten, J., & Kassell, N. (1997). Cooperative bimanual action. *Proceedings of the CHI'97 Conference on Human Factors in Computing Systems*, 27-34, New York: ACM.
- [7] Hinckley, K., Pausch, R., & Proffitt, D. (1997). Attention and visual feedback: The bimanual frame of reference. *Proceedings of the 1997 Symposium on Interactive 3D Graphics*, 121-126, ACM.
- [8] Hinckley, K., & Sinclair, M. (in press). Touch-sensing input devices. To appear in the *Proceedings of the CHI'99 Conference on Human Factors in Computing Systems*. New York: ACM.
- [9] Kabbash, P., Buxton, W., & Sellen, A. (1994). Two-handed input in a compound task. *Proceedings of the CHI'94 Conference on Human Factors in Computing Systems*, 417-423, New York: ACM.
- [10] Krueger, M. (1991). VIDEOPLACE and the interface of the future. *The Art of Human Computer Interface Design*, ed. Brenda Laurel, 417-422, Menlo Park, CA: Addison Wesley.
- [11] Kurtenbach, G., Fitzmaurice, G., Baudel, T., & Buxton, W. (1997). The design of a GUI paradigm based on tablets, two-hands, and transparency. *Proceedings of the CHI'97 Conference on Human Factors in Computing Systems*, 35-42, New York: ACM.
- [12] Leganchuk, A., Zhai, S., & Buxton, W. (in press). Manual and cognitive benefits of two-handed input: An experimental study. To appear in *ACM Transactions on Computer-Human Interaction*, New York: ACM.
- [13] Zeleznik, R. C., Forsberg, A. S., & Strauss, P. S. (1997). Two pointer input for 3D interaction. *Proceedings of the 1997 Symposium on Interactive 3D Graphics*, 115-120, New York: ACM.