Tactile Computer Graphics

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Abstract

The term "computer graphics" has traditionally been used to denote visual output on a screen or a printer. Outside of computer science, however, tactile representations have been used in areas such as cartography for representing information to augment visual presentations.

In this paper, we analyse the difference between the design of visual and tactile images. We report on the image manipulation functionality required of graphics systems which are to be able to produce tactile graphics. Finally we present a rendering/editing system for tactile graphics intended for blind users.

1. Introduction

The term "computer graphics" has been used to refer to images produced for visual inspection on computer screens, paper or on other media like celluloid and foils. In recent years, the computer graphics community has extended its interests to include richer interaction, such as is now found for example in virtual reality systems. Of interest is no longer just the visual impression but also sounds and users' movements to accompany interactive graphics.

One topical area of interest for which solutions are not yet well established is force feedback. There is still room for improvement in practically all phases of the software and hardware output which users can feel. This extends from theories related to what kind of feelable output is desirable in what tasks, all the way to developing safe and effective methods and devices for actually carrying out the movements.

One - albeit specialised - subproblem within this general area is that of producing tactile graphics. The goal is to be able to generate images which users can understand by simply running their fingers over them. Yet users need not be restricted to such touch: Questions pertaining to the superposition of colour images with tactile portions quickly arise. How can colours and raised surfaces augment one another in computer output? Such effects are used today only in some maps made by hand, in which for example mountains are actually represented by raised portions of material. Having such facilities in computer output could further enhance for example the display of statistical data, the results of scientific computing and handbooks for technical devices.

Our interest in this topic stems from more modest research goals, however: We wish to generate images which can be touched by blind users who need primarily the tactile component in the output. At first glance one may conclude that the problem is very simple: Raise the lines of conventional wire-frame output with suitable hardware, or raise the edges of objects visible in a photorealistic image. However, as we will demonstrate in this paper, images which are to be touched and understood by blind persons must be designed differently than images which are to be understood by visual inspection alone. This means that graphics systems require a new functionality if the output is to be in a tactile form.

A natural question to ask is, are there enough blind persons around to warrant widespread attention being paid to this problem within the computer graphics community? The number of persons affected is only approximately 0.2% of the population in the western world; the figure is higher in the third world. On the one hand, a deeper understanding of this problem can serve as a basis for the use of tactile elements in images for sighted users, as suggested above. On the other hand, demographic statistics show that in the western world, there are even more blind and visually impaired persons than university graduates of computer science! Moreover, only about 5% of blind persons in western countries are proficient in Braille, since many are elderly or have other handicaps which make it difficult for them to learn Braille. Hence the ability to feel forms is an important element of their communicative repertoire.

The paper is organised as follows. Chapter 2 surveys background literature on the topic of force feedback, tactile graphics and blind users. In Chapter 3, we carry out a case study in which we compare a drawing intended for sighted persons with a drawing of the same scene produced in a tactile form for a blind person. The differences between the two define the tasks to be carried out by a renderer for generating tactile graphics. Next we discuss the availability of graphical materials and the actual needs of blind persons. We conclude that relatively few materials exist in the form of models. Hence Chapter 4 describes software for constructing computer models of objects drawn as a certain class of images. We then turn in Chapter 5 to the description of a rendering/editing system in which a sighted user is supported in his task of producing adequate tactile graphics from models. Concluding remarks and suggestions for further work are discussed in Chapter 6.

2. Background

2.1. Force Feedback and Tactile Output

Currently there are two classes of haptic output in the field of computer graphics: force feedback and tactile graphics. While the former enables a certain degree of interactivity, the latter is much more accurate and conforms more to the every-day-experience of touch. However, to date there is no usable, operative *interactive* device to give the user the opportunity of interaction as well as comfortable and accurate output.

2.1.1. Force Feedback

In the context of virtual reality applications, data-gloves are popular input-devices. Thus it is only logical to use the same device for (tactile) output, too. Several attempts in this field have been made.

In a first approach, a conventional data-glove was equipped with small cushions at the end of each finger. These cushions can be filled with air at various levels of pressure which gives the person wearing the glove the impression of resistance at his fingertips. Controlling the air pressure in the cushions by the Virtual Reality (VR)-System results in a quite "natural" use of the hand as actor (glove as input-device) and sensor (glove as output-device) (see [Shimoga 93b]).

An other approach to come to the same result was to connect the data-glove to a mechanical framework with a hinge at each knuckle of the fingers. The hinges are controlled by the VR-System preventing the user from closing his fingers if he touches a virtual object (see also [Shimoga 93a] for a similar method).

Neither of the above approaches give very accurate feedback. In particular, the user can not feel the texture of an object and he can not scan a larger object like a chair or even the wall of a room.

Minsky et al. [Minsky 90] describe a "Sandpaper" System which is intended to give the user an (indirect) impression of a virtual surface-texture. A motor-driven joystick with two-degrees of freedom is used as the interaction device. Whenever the joystick is positioned on a sloped spot of the virtual surface (which is the case nearly always since the investigated surfaces were not smooth) the software computes the appropriate forces for the joystick-motors "to pull it downwards". This way a user can scan a surface using the joystick. One of the main advantages of this approach is the fact that textures are found to be important for tactile displays. We will return to this later.

A system to manipulate virtual solid objects using 9 degrees-of-freedom-device was described by Iwata [Iwata 90]. The user's hand is put into a mechanism, called the "Master manipulator", which now induces forces onto the thumb and two groups of fingers. This way the user has the impression that he is grasping an object. The system is limited to a very small area of use since the user can hardly translate his hand.

An approach for more spacious applications was presented by Brooks et al. [Brooks 90]. They provide the user with a hand grip attached to a mechanic arm. The hand grip can be moved in 6D to place a virtual molecular model next to another. The resulting intermolecular forces are calculated and presented to the user as force-feedback: the hand grip cannot be moved to a position which would be impossible with respect to chemical restrictions. There is no fine-grained texture-feeling but the user can scan objects (molecules).

The above systems provide real-time force-feedback, but do not the presentation of tactile graphics. For this purpose, a variety of off-line-techniques have been developed. These will be described in the following section.

2.1.2. Tactile Output

The easiest way to produce tactile graphics is with a strong dot-matrix-printer and a thick kind of paper. The printer's pins make small dents into the paper. If one turns the paper around, its back subsequently has raised spots which are feelable. Using this method, one can easily produce dotted lines and textures on paper. However, it is not possible to produce full lines or even different styles of lines.

Another quite simple way is the use of so-called swell-paper (also termed micro capsule or Minolta paper): The graphics are drawn (or printed) on normal paper. A copy of the drawing is then made through a photocopy machine on the swell-paper. Swell paper contains a layer of encapsulated resin particles which swell under the influence of heat. The copy on swell paper is heated in an adequate oven. The heat of the oven is absorbed by the (black) ink on the swell paper and the resin micro capsules directly under the ink layer swell, thereby providing the relief on the paper, i.e., become touchable when one runs one's fingers over the graphics.

Yet another method was explored in a somewhat more elaborate procedure, requiring special equipment. This entails covering with wax the areas to be drawn on. This procedure, called thermography, is also used to produce some fancy business cards. Here, the resin particles are blown over the printing ink when it has just been printed and still wet. The particles then stick to the ink. The surplus of particles is removed by aspiration, and the page with the wet ink and resin is then heated. The ink dries and the resin swells.

In a totally different approach, a prototypical device was built to plot line drawings on paper using a plotter which was enhanced with a special pen and a heating system: the pen plots the drawing on paper using so called puff-ink. Afterwards, the heating system is moved over the paper and the ink, causing the ink to "puff", i.e. to swell (see [Rathgeber 90]).

For human-computer interaction, various devices have been built to allow blind users to obtain information in a tactile form. For normal texts, special output Braille devices are available. For example, the 2D Screen Reader from FHP (Schwerte, Germany) can display two 80-character Braille lines. On this device, each Braille character consists of eight pins which can be raised or lowered.

For displaying computer graphics for blind users, a "pin matrix" device was constructed at the University of Stuttgart (see [Schweikhardt85]). This device has about 7000 pins which are arranged in a rectangular fashion and can be raised and lowered individually. Graphics are displayed as a result of a dialogue, in which a blind user can obtain information with respect to attributes of the pixels, such as their colours. Thus the user can, for example, ask the machine to raise all pins corresponding to pixels coloured red or green in the graphics on the screen, while leaving all other pins lowered. The device was initially used for displaying videotex pages to blind users.

2.2. Blind Computer Users

With the widespread introduction of computers in the 1980's, new office jobs for blind people were created (in Germany alone several thousand). These blind employees gained access to conventional text-based programs running on a PC or terminal using technical aids. More specifically, these are devices which convert the text displayed on the screen into acoustic or tactile signals. The area of memory which contains the screen-contents (in an ASCII-format), is read, and the letters found are presented via speech-synthesis (acoustic) or using a Braille-display (tactile). Programs providing such services are essentially user interfaces, called screen-readers. Further information on this topic and an example can be found in [Ford 91].

The increasing use of graphical user interfaces (GUI's) poses problems to blind persons (see [Gill 93]). Conventional screen-readers can read and present only text-based screen contents. GUI's are based not on text, but on graphical information stored as a bitmap. Even in places where text is displayed on the screen, usually only the shape of the letters is stored in the screen memory, not an ASCII-representation. This results in a number of problems for visually disabled users, both for input to the computer and output from the computer. Indeed, blind persons risk loosing many of the jobs they gained in the 80's because of the technological advancement in user interfaces.

Research and development is underway to provide blind people access to GUIs. Both acoustic as well as tactile output are being considered (see

[Strothotte 93]). The idea is that an "offscreen" model is constructed by the system, which describes in a symbolic fashion what is on the screen. The blind user can interrogate this model to obtain the necessary information. It is a tedious process, although it works for all screen contents with the exception of graphical images. Hence for such screen contents, alternative output mechanisms must be sought.

3. Visual and Tactile Graphics: A Comparison

Starting with the assumption that visual and tactile graphics should transport about the same information, we have to look more carefully at the way a tactile graphic is perceived in comparison to a visual one.

First, both kinds of graphics have several characteristics in common:

- Graphics are two-dimensional. They require and they use a certain area on the medium (paper, screen or another).
- Graphics consist mainly of dots (points), lines and (textured) areas.
- Objects which are physically close to each other in the real world are (usually) close together in the corresponding graphics as well.
- Graphics can express their producers' *intention* directly or subtly.
- *Pleasure* can be one of the most important effects of graphics. Thus blind people often have tactile images hanging on their walls the way sighted persons enjoy having visual ones

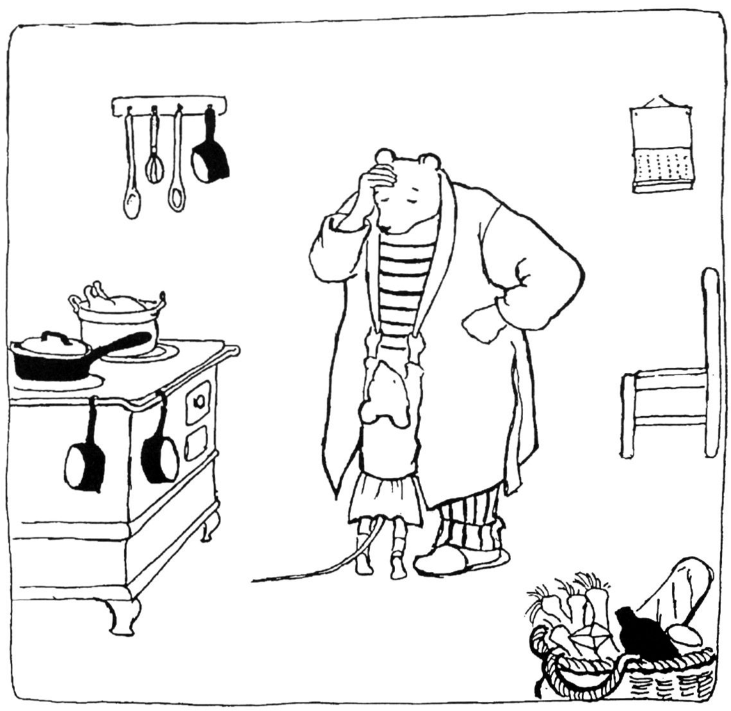
Then again the way visual and tactile graphics are perceived is different:

Visual graphics are looked at and understood in a very short time. The eye usually finds out the most important places of the image very quickly. The perception is two-dimensional.	Tactile graphics are scanned linearly, line by line and dot by dot. This is a time-consuming process. It is not guaranteed that the "viewer" can in fact find the most important area at all. The perception is largely one-dimensional.
The eye is able to recognise very small details.	The human sense of touch is limited to a minimum distance of points touchable of about 1.5 to 2 mm.
Colours and patterns are additional dimensions to see in visual graphics.	Texture and temperature are of similar meaning for tactile graphics

Figure 3.1 shows an example of a visual graphic (a) and a tactile one (b), taken from a childrens book [Vincent 91. The setting is that a sighted adult tells the story to a blind child. This example will help us discover important differences between these kinds of images.

- Most objects are drawn in *less detail* (for example the stove).
- Some *redundant* or unnecessary objects can be *removed* (some of the vegetables, the back wall).
- Objects *partially hidden* by others are removed (the right leg of the bear).
- *Graphical effects*, such as shadows, are removed; others may be added to enhance tactile recognition (for example the calendar on the wall).
- Some (important) lines are drawn *thicker* to draw the attention to them (texture on the bears shirt).
- Some lines may be *added* to the graphic to make spatial relations between objects clear.
- Some objects may need to be *moved* to a different place (the pans hanging on the wall).
- Objects in the visual graphic may be *replaced* by different objects in the tactile form to help the viewer to distinguish them from others.
- The *point of view* of the whole scene or just for some objects may be different in the tactile form to make the tactile recognition easier (for example the chair).

a)



b)

Figure 3.1 Sample image from a childrens book [Vincent 91]
a) An image produced for a sighted person
b) a tactile image, reproduced in black and white, of the same scene, produced for a blind person

This enumeration shows that graphics designed to be viewed by sighted persons ought not simply be scanned and converted into a tactile form for tactile perception (see [Edman 92]). Instead, the pictures must be transformed into a new form, paying attention particular to

- details which might be redundant/unnecessary or too vague or complex,
- the characteristic features of a tactile graphic, in particular to the fact it is a two-dimensional representation of a three-dimensional scene which is perceived one-dimensional fashion.
- additional details to ease the recognition of items or persons for the tactile perception.

Concluding this chapter, we summarise that tactile graphics must be rendered in a different manner then visual graphics.

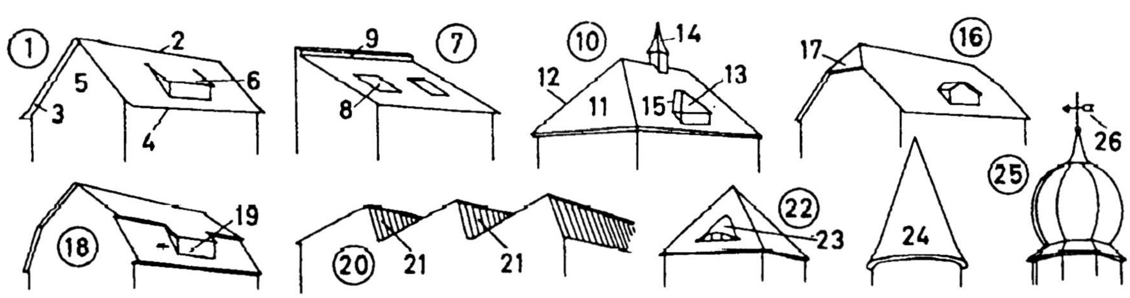
4. Constructing 2D/3D Models

The vast majority of graphical images which are generally available and of potential interest to blind persons are printed on paper and not - as computer scientists would like to have it - accessible in the form of computer models. However, the kinds of manipulations required on visual graphics to turn them into a form which can be understood as tactile images clearly requires an underlying model. It is not reasonable in any practical setting to expect a sighted person to construct a 3D model using conventional modelling tools for every scene which may be needed by a blind person. This means that if we "only" write rendering software to produce tactile images, we are solving a purely academic problem of little or no practical relevance. Thus this Chapter is devoted to reporting on modelling software which we designed and implemented for a particular class of graphics. We provide only a brief overview; details may be found in [Kugas 93].

We set out to devise modelling software which allows a sighted user to construct a model, assuming he has at his disposal an image on paper. The model is to be 3D for those objects or parts thereof for which manipulations are later necessary to produce a tactile image; for the rest, 2D models are to suffice. We refer to such models as 2D/3D models. We restricted ourselves to the class of images found in the DUDEN/OXFORD picture dictionary: accurate line drawings primarily of objects, augmented by numeric labels and a legend giving the name of the objects and parts thereof (see Figure 4.1 for an example).

Our procedure for interactively constructing a 2D/3D model is then as follows:

1. The (sighted) user scans the image of interest



Legend:

1 gable roof	8 skylight	15 valley (roof valley)	22 broach roof
2 ridge	9 fire gable	16 hipped-gable roof	23 eyebrow
3 verge	10 hip (hipped) roof	17 partial hip end	24 conical broach roof
4 eaves	11 hip end	18 mansard roof	25 imperial dome
5 gable	12 hip (arris)	19 mansard dormer win.	26 weather vane
6 dormer window	13 hip dormer window	20 sawtooth roof	
7 pent roof	14 ridge turret	21 north light	

Figure 4.1 Extract from the DUDEN/OXFORD picture dictionary [Duden 79] showing some objects and the legend to go with them

into the computer using standard software (Figure 4.2).

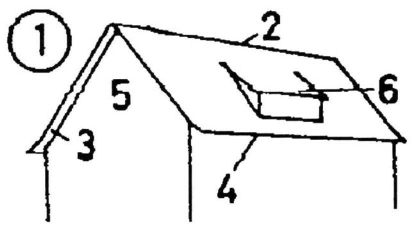


Figure 4.2: Sample image

2. OCR Software is used to convert the labels on the objects and the legend into an ASCII-version. The user can compare the original with the ASCII-version and make correction as necessary.

3. Standard vectorization software is used to analyse the graphical portion of the image. This produces a 2D vectorization; we implemented software to allow the user to make corrections in the vectorization as deemed necessary.

4. The ASCII-labels are associated with the surfaces and lines of the object by an appropriate interpretation of the image. These extra symbols are then removed, leaving behind only the image of the object (Figure 4.3).

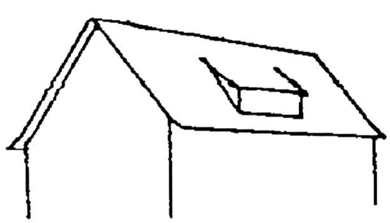


Figure 4.3: Object without extra symbols.

5. The system constructs a series of equations describing possible 3D interpretations of the 2D vectorization. These equations contain unknowns (variables) to account for the third dimension.

6. The user carries out simple manipulations to solve for the unknown in the equations of 5, thereby converting parts of the 2D vectorization into a 3D model.

Steps (1) to (3) are straight forward, steps (4) and (5) require more detailed explanation. Consider the perspective view of a house as illustrated in Figure 4.2 Since the machine has no *a priori* knowledge about the object, it is not possible to construct any data structure but the 2D vectorization. And yet to a human viewer, a great deal of information is obvious, for example which surfaces are at 90 degrees to one another, and which are not; and which lines that appear not to be parallel to one another but are in fact parallel.

We provide the user with a simple set of manipulation primitives and predicates in order to specify information pertaining the 3rd dimension. The user can

- select two or more lines

and give them one of the following attributes:

- are parallel to one another,
- define a plane, or
- are perpendicular to one another.

Furthermore, the user can select

a) points, lines or planes, and

b) a plane

and combine them with the predicate "a) lies in b)".

The user can also select two planes and

- specify the angle between them, most often 90 or 180 degrees.

Finally the user can identify pairs of lines and specify that they are analogous, thereby enabling the construction of a 3D model of hidden parts based on symmetry assumptions.

An essential feature of our modeller is that the user can choose to leave parts of his image unmodelled in 3D, i.e., he can simply use the 2D representation where he wishes. These will then be treated by the system as two dimensional drawings on a clear glass plate within the 3D model. This is particularly useful for such parts of the image as either require no transformation into another form for the tactile output, or where the modelling would require an unreasonable amount of effort and the user is prepared to accept a certain loss in quality of the tactile output at the price of not carrying out the complete modelling process.

At any time, the user can skip into a conventional 3D modeller which we wrote for the present purpose. The user can view the current state of the model as he has constructed it and update parts with the usual features of rotation, copying etc. (see Figure 4.4); details may be found in [Raab 93].

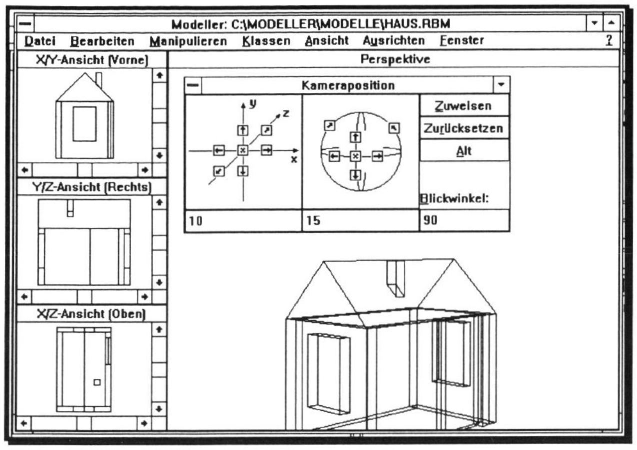


Figure 4.4 Screen dump of the modeller

5. A Rendering/Editing System for Tactile Graphics

Assuming that there now exists a 2D/3D model for the scene to be rendered, the system is responsible for producing a tactile image, paying particular attention to the points addressed in Chapter 3.

At this moment, we should point out that the disportions introduced in a tactile image due to our rendering-editing-system can be found in some visual graphics too. Fig. 5.1 shows an example of a drawing from the middle ages where this technique was used. Today such images are still found in childrens´ books.

Two possible approaches can be taken:

1) We can assume that a sighted user (to avoid confusing him with the blind viewer, we shall refer to him as the "designer") takes on responsibility for making sure that the output is in a form which can be understood by a blind user touching the output. In this case the system ought to draw possible problematic points to the attention of the designer and provide him with the manipulative capability to rectify the situation. Alternatively,

2) we can assume that the blind user is working alone, so that the system is to make every effort to produce an image which is understandable directly by the blind user without intervention.

Fig. 5.1 A medieval drawing showing a goldsmith at work using more than one perspective.

The architecture of the rendering/editing system which we have designed and implemented is shown in Figure 5.2 The touch-renderer accepts as input the usual model, but in addition a data structure which we refer to as the "tactile configuration". This describes the modification to the scene which must be undertaken so as to bring it into a form which can be understood in a tactile form.

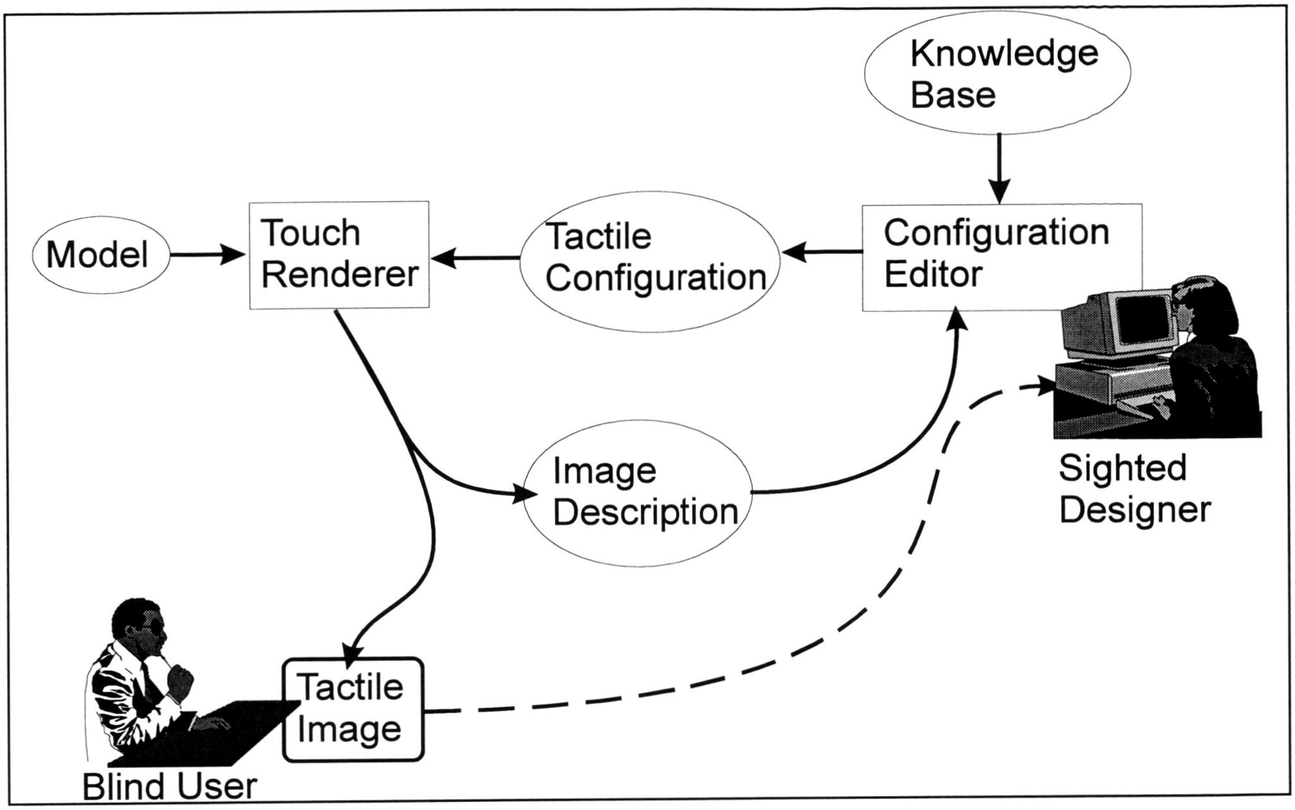


Figure 5.2 Architecture of the tactile rendering/editing system

These modifications include:

- change of camera position just for a single object,
- removing visible surfaces in the background so as to make the foreground more clearly distinguishable,
- removing certain detail which would confuse the tactile image or be too small to be recognisable, and
- changing the size of objects and moving them around so as to make the overall image more understandable.

The knowledge base contains heuristics for recognising problematic aspects of an image, which if there is no sighted designer, determines the tactile configuration autonomously.

In the case that there is a sighted user (designer) available, the confutation editor points out its observations to him and provides him with facilities to modify the image.

The system works in a cyclic fashion. Initially the tactile renderer produces a first image with an empty tactile configuration. This corresponds to the usual wire-frame-like image with hidden line removal. Besides this first image, the renderer also produces an "image description", much like the hyper-renderer [Emhardt 92] which contains a symbolic description of what is represented in the output. This in turn is read into the configuration editor which analyses this representation of the image and with the help of the knowledge base and perhaps the sighted designer produces a new tactile configuration. This process is repeated until the images can no longer be tuned further. Finally, the line-drawing on the screen is output on paper an transferred to swell paper (recall chapter 2.1.2) so it can actually be touched by the user.

Figure 5.3 (a) shows a sample scene as it was produced initially and 5.3 (b) shows the image after the designer finished his editing procedure. It may appear odd to a sighted person, however, it corresponds to the principles derived in Chapter 3. Blind persons do not think of the combination of different camera positions in one image as a contradiction.

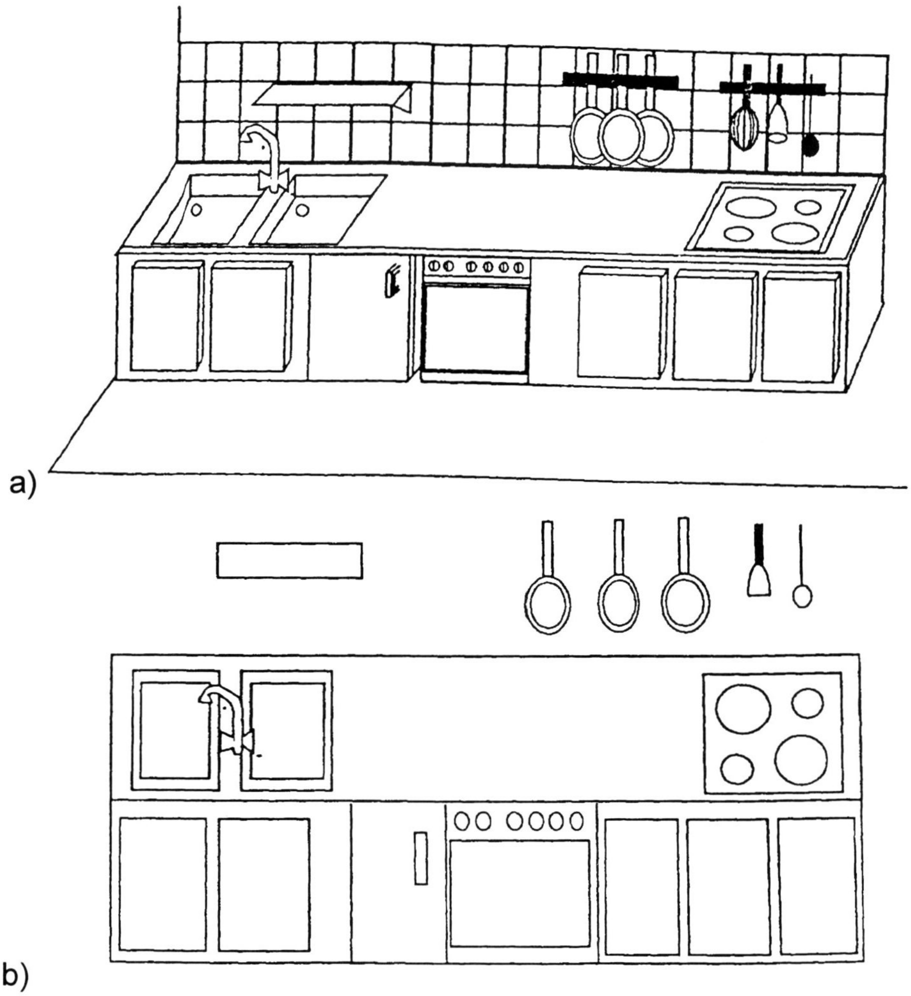


Figure 5.3 (a) original wire-frame and (b) tactile output produced for the blind user.

6. Concluding Remarks

In this paper we have identified key features of tactile graphics intended for blind persons and developed methods by which tactile graphics can be supplied to such users.

The key observation made is that tactile graphics for blind persons are very different in form from the usual visual graphics. Care must be taken to avoid such features as overlapping regions, perspective and small items. Ideally, a human designer should be involved in the editing process which is supported by a knowledge base. If the blind user wishes to work autonomously, the system we implemented will make the design decisions itself.

This work is to be seen in the larger context of tactile output in multimedia and VR systems. Where force feedback can be used to provide a small amount of information pertaining to the values of selected variables, tactile output like we suggest in this paper can be used for more complex forms. Ideally we would like to have tactile graphics be more interactive; however, it is still an open problem to design such hardware technology. We envision the use of a material which can be formed and deformed quickly by the computer.

Having gained experience in generating tactile graphics for blind users, the next step is to generate images which are both visual and tactile for sighted persons. This would not only enable a user to gain more information by touch about the scene or data being displayed, it can also serve to add to the visual effect of the image. If light is projected onto such images, shadows will result which provide another dimension to their interpretation.

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