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Stereoscopic Non-Photorealistic Rendering

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Abstract

Communication of spatiality in 2D visual arts has been a central topic around which artistic experimentation has flourished for centuries. The inherent limitation of "flatness" governing most traditional visual media has proven to be fertile ground for the emergence of advanced pictorial techniques (e.g. linear perspective) that attempt to counter it. Despite the multitude of pictorial techniques developed, handcrafted works of art (e.g. paintings, drawings, etc.) that adequately provide monocular depth cues often fail to capture the vibrancy and plasticity of a truly three-dimensional world and, in addition, may poorly engage and immerse the observer. In contrast to these techniques, stereoscopy has been instrumental in vindicating that monocular depth cues alone were insufficient for our visual system to infer robustly depth and spatial relations from a single picture. However, while stereoscopy was adopted soon after its discovery by the scientific community, only a relatively small number of fine artists have studied and used this peculiar medium for artistic purposes. The use of stereoscopy in fine arts enabled artists to create paintings and drawings that could detach from the flat surfaces they were laid on and float directly in front of the observer's eyes, opening a whole new world of possibilities for artistic experimentation.

As stunning an experience of seeing stereoscopic artworks as it is, the creation of these dual works is a rather tedious and laborious process. The artist not only has to create the artwork twice from slightly dissimilar vantage points, he is also required to preserve feature and color correspondences between the two projections with great care, without introducing artifacts that might hinder stereoscopic fusion. In the digital era, abundant computational methods have been developed to create monoscopic images that resemble artwork, using as an input either 3D models or images. Despite the high availability of such algorithms, hardly any research has been done so far in the area of artistic stereoscopic rendering from real images.

The work presented in this dissertation provides a stepping stone in the direction of combining computer graphics and vision techniques to form novel image-based stereoscopic Non-Photorealistic Rendering algorithms. These algorithms can be used to transform photographic stereoscopic images into pairs of pictures that resemble stereoscopic drawings, cartoons or paintings. Central to all our algorithms is the use of stereo correspondences, calculated by using stereo matching algorithms. These correspondences, usually encoded in a disparity map, are used to propagate style

that is synthesized in the geometry of one stereo view to the other, thus preserving the consistency of the texture across the two views of a stereo pair. In addition, the disparity map is utilized in order to identify image areas, known as occluded regions, that are not visible from both views simultaneously, and thus style generated in one view cannot be propagated in these areas using stereo correspondences. Instead, in these occluded regions texture synthesis procedures specifically generate stylized texture that seamlessly blends with the texture of surrounding non-occluded regions, within the same stereoscopic view.

Furthermore, the artistic-looking stereoscopic image pairs generated using our algorithms provide a basis over which a set of interactive methods and tools are built to enhance the experience of viewers. We provide a way to manipulate stereoscopic space by simple adjustment of the separation of the two image projections, and we demonstrate the use of the disparity map as a means of automatically choosing optimal separation values in order to reduce eye-strain. In addition, we describe the design of a stereoscopic cursor and a magnifying glass that can be used to inspect the stereoscopic results generated by our system. Finally, we expose viewers to a new method of interacting with computer-generated stereoscopic paintings that enables them to slice through the painting and observe the understructure of the work.

The novel algorithms presented in this work set the foundation to harnessing stereoscopy as an artistic medium within the context of image-based computer graphics and vision, and their results may find utility in the game, media or film industries.

Kurzfassung

Die Darstellung von Räumlichkeit ist eines der zentralen Themen der zweidimensionalen bildenden Kunst, welches jahrhundertlang Inspiration für künstlerische Experimente lieferte. Die inhärente "Flachheit", die einen Großteil der klassischen bildenden Kunst beherrschte, war ein fruchtbarer Boden für die Entwicklung fortgeschrittener Darstellungstechniken, wie z.B. der perspektivischen Darstellung. Trotz der Vielzahl der entwickelten Methoden können Zeichnungen und Gemälde, die zwar monokulare Tiefeninformation adäquat bereitstellen, die Lebendigkeit und Plastizität einer tatsächlich dreidimensionalen Welt oft nicht befriedigend abbilden und involvieren den Betrachter nur unzureichend in die Szene. Das Aufkommen von Stereoskopie trug maßgeblich zur Erkenntnis bei, dass monokulare Tiefeninformation für unser visuelles System nicht ausreichend ist, um robust Tiefe und räumliche Zusammenhänge aus einem einzigen Bild abzuleiten. Während die Stereoskopie bereits bald nach ihrer Entdeckung von der Wissenschaft aufgegriffen wurde, wurde sie nur von einer relativ kleinen Anzahl von Künstlern studiert und angewandt. Die Anwendung der Stereoskopie in der darstellenden Kunst ermöglichte erstmals die Schaffung von Gemälden und Zeichnungen, die sich von der Fläche lösten und direkt vor den Augen des Betrachters zu schweben schienen. Dadurch erschloss sich eine ganze neue Welt für künstlerische Experimente.

So überwältigend die Erfahrung bei der Betrachtung eines stereoskopischen Bildes auch ist - die Erzeugung dieser Zweifach-Darstellungen ist ein langwieriger und arbeitsintensiver Prozess. Der Künstler muss das Bild nicht nur zweimal, aus jeweils leicht unterschiedlichen Blickwinkeln, kreieren, sondern muss auch sehr sorgfältig die Korrespondenz von Strukturen, Merkmalen und Farben zwischen beiden Projektionen herstellen, um eine korrekte stereoskopische Verschmelzung sicherzustellen. Im digitalen Zeitalter wurden bereits viele Methoden entwickelt, die, z.B. auf Basis von 3D Modellen oder Fotos, monoskopische Bilder generieren, die Gemälden, Graphiken oder Zeichnungen ähneln. Trotz der Verfügbarkeit dieser Algorithmen wurde bis jetzt nur wenig im Bereich automatische Generierung von künstlerischen stereoskopischen Bildern auf Basis von Fotografien geforscht.

In dieser Dissertation werden Methoden aus Computergraphik und maschinellem Sehen zu neuen bildbasierten, nicht-photorealistischen, stereoskopischen Rendering Algorithmen kombiniert und so eine Basis für weitere Entwicklungen geschaffen. Diese Algorithmen können verwendet werden, um aus stereoskopischen Fotografien

Paare von Bildern zu generieren, die stereoskopischen Zeichnungen, Cartoons oder Gemälden ähneln. Kern der hier entwickelten Methoden ist die Verwendung von Stereokorrespondenzen, die durch Stereo Matching Algorithmen berechnet werden. Diese Korrespondenzen, die gewöhnlich mittels Disparitätskarten beschrieben sind, werden verwendet, um eine Konsistenz der Textur in beiden Bildern des Stereopaares zu erreichen. Zusätzlich wird die Disparitätskarte dazu verwendet, sogenannte verdeckte Bereiche des Bildes zu erkennen, die nicht aus beiden Blickrichtungen gleichzeitig gesehen werden. In diesen Bereichen können Renderingstile nicht durch Stereokorrespondenz übertragen werden. Stattdessen wird in diesen Bereichen durch Textursynthese neue Textur generiert, die innerhalb derselben stereoskopischen Ansicht nahtlos in die angrenzende Textur sichtbarer Regionen übergeht.

Die künstlerisch anmutenden stereoskopischen Bildpaare, die mit Hilfe der entwickelten Algorithmen generiert wurden, bilden die Basis, auf der eine Anzahl von Methoden und Werkzeugen entwickelt wurden, die dem Betrachter eine interaktive Erfahrung und Erforschung des Bildes ermöglichen. Es wird dem Benutzer eine Möglichkeit zur Verfügung gestellt, durch einfache Anpassung der Position der beiden Augpunkte die Tiefendarstellung zu adaptieren. Dabei wird auch die Verwendung der Disparitätskarte zur automatischen Berechnung optimaler Abstandsparameter demonstriert, um die Augenbelastung zu reduzieren. Zusätzlich wird das Design eines stereoskopischen Cursers und einer Lupe beschrieben, welche die Möglichkeit bieten, die generierten Ergebnisse zu inspizieren. Schließlich wurde eine neue Methode zur Interaktion mit stereoskopischen Bildern entwickelt, die es erlaubt, durch die einzelnen Schichten eines generierten Bildes zu blättern, um die zugrunde liegende Struktur zu erkennen.

Die neuen Algorithmen, die in dieser Arbeit vorgestellt werden, legen den Grundstein für die Verwendung von Stereoskopie als künstlerisches Medium im Kontext bildbasierter Computergraphik und maschinellen Sehens, deren Ergebnisse nützliche Anwendungen in den Bereichen Spieleindustrie, Multimedia- und Filmindustrie finden können.

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Contents

Chapter 1

Introduction

The expressive depiction of 3D information onto 2D surfaces has been for centuries a central matter in pictorial visual arts. The intent of artists widely varied together with the associated techniques that were developed to record scenes and events taken from everyday life, to make portraits of important individuals or even to document well-known processes and ideas of their time. Prior to the invention of the photographic process, artists have been mainly projecting 3D visual stimuli on 2D surfaces by developing and using various artistic media and techniques. Mastering these pictorial techniques has been instrumental in the rise of life-like representations of three-dimensional scenes on flat surfaces, regardless of whether artists attempted to accurately depict reality as this could be objectively seen or they strove to enrich or abstract it.

This 3D to 2D projection imposes a natural reduction in the number of degrees of freedom, since one dimension is discarded. The impact of discarding the third dimension in order for it to be represented in a 2D form is multifaceted and has become a point of intersection between a variety of disciplines across both arts and sciences. The experience of reducing the dimensionality of 3D spaces has propagated from pictorial arts to the science of optics and, subsequently, to photographic techniques and later to digital imaging, computer graphics and visualization.

The desire of artists to accurately communicate pictorial depth led them very early into the development of advanced techniques that could be used to make captivating artwork. For centuries the use of monocular depth cues, such as shading, linear perspective, etc., has been common practice among picture makers. It was mainly through refinement of the old understanding and techniques that pictures became more vivid along the history of visual arts. After the Renaissance (14^{th}–17^{th} c. AD), it was mainly the discovery of stereoscopic vision in the 19^{th} century that provided new insight into the ability of humans to see depth. Unlike other techniques for handcrafting pictures, stereoscopy did not become as popular and remained mainly as a technique that flourished along with the, almost concurrently developed, photographic process.

In arts only a small number of artists using traditional media have adopted stereoscopy in order to handcraft artistic works that robustly communicate spatial relationships within a depicted scene. Mainly due to technological advancements, the popularity of stereoscopy has seen until today many “rise and fall” eras. Even going a long way from the invention of the first handheld stereoscopes to our contemporary digital stereoscopic devices, the immense artistic potential of stereoscopy remains to be unlocked. The key probably is not the artist who is armed with a new technique for creating artwork, but most likely it is the viewer whose status changes within a stereoscopic context. The viewer is no longer a mere third-party observer, he is reinstated in regard to the stereoscopic artwork as a *participant* who not only will be immersed and detached from the immediate real world while viewing stereoscopic content, but he can establish a sense of presence and relate – at least spatially – to the artwork.

The stereoscopic medium encompasses technicalities that require artists to become familiar with and fastidiously exercise this knowledge taking a step further from the commonly used methods. They are now required to learn how to create stereoscopic pictures by hand and, most importantly, how the audience will perceive them. The plethora of technical subtleties and the finicky details surrounding the aesthetics of this medium present artists with a very challenging art form. As it will become apparent in subsequent chapters of this dissertation, stereoscopic arts and especially the associated aesthetics are a largely unexplored territory.

Taking a technical approach to this vast subject, this dissertation aims to increase the awareness of both scientists and artists regarding the ability of the stereoscopic medium to communicate artistic content by utilizing state of the art technological advancements in computing that were unavailable to the pioneers of traditional stereoscopic artwork. Thus the work presented here can potentially motivate scientists to further pursue the development of technical tools for artistic stereoscopic content creation and simultaneously entice artists to reinstate stereoscopy in their creative toolset.

1.1 Background and Terminology

1.1.1 Images and Pictures

Forming visual representations, referred to as images, has been the main focus of photography and computer graphics in recent years. Pictures and images are usually interchangeably used to refer to generated 2D representations of real or virtual 3D objects. The question itself of what an “image” is, is not an easy one to answer. It becomes even more difficult to provide a thorough explanation if the notion of a "picture" is implicated in this subtle clarification.

As Mitchell [73] discusses, it depends from which standpoint one understands the meaning of these words. Images form a larger family of representations. For instance there are graphic images, optical images, but also perceptual, mental and verbal images. Each of these categories embodies ideas of the respective discipline within which it functions and takes further meaning. Images are not considered purely as a material object, the function of the word usually suggests "likeness" and is referring more to the actual represented subject and any associated meanings or ideas of it and less to the material body of the surface and the physical marks deposited on it.

Panofsky [77, p.5] identifies three levels of understanding pictorial representations and, particularly, works of art. The *primary or natural subject matter*, the *secondary or conventional subject matter* and the *intrinsic meaning or content*. The first level refers to the basic meanings the material body of the representation suggests. The colors and lines combine into forms that are understood in their basic factual and expressional qualities, such as material objects (e.g. humans, animals, etc.) or gestures and events (e.g. mourning, peaceful atmosphere, etc.). The second level attaches conventional knowledge of iconography and cultural orientation of the viewer to the forms of the imagery. Thus it is easy for a Western viewer to recognize religious figures in paintings and icons of Christianity, for example. The third level Panofsky lays out is that of intrinsic meaning and content. This last level goes beyond mere recognition of compositional elements of the image and the identification of the conventional subject matter. In this level, the viewer seeks to understand the sociocultural motives of the artist of the composition. It is the level on which the underlying meaning of the artwork can be identified and uncovered in the scope of the historical and cultural understanding within which it was executed.

In the context of the discussion herein a distinction is made between "images" and "pictures". When looking at the particular words of "image" and "picture", a literal distinction can be made. An image has various meanings, such as a copy, an imitation, as well as a depiction, while a picture is more specifically targeted to describe an artistic visual representation. Note also that etymology suggests that "image" stems from the Latin *imāgō*, which is akin to the Latin *imitāri* (to imitate), while "picture" is derived from the Latin *pictūra*, which means painting [60].

In computer science, however, an image is almost always a digital material quantity that is codified into bits. The term is used in a strictly technical context. It is common for computer graphics and vision scientists to "acquire", "process", "transform" or "render" *images* and not pictures. In contrast a photographer, even though literally will create images with his camera, will usually "take a picture", rather than an image. This is because a photographer will interfere with the actual process of image-making. It is not just the mechanical parameters of the device used that turns an image into a picture, it is also the selection of the subject, the angle and the frame which will be chosen for any given photograph that turns it into a picture. It is the *intention* of the photographer and scientist that proposes an appropriate term used to describe essentially the same thing.

When considering the interaction of light with 3D surfaces at a specific time and a single fixed viewpoint, there is generally one 2D image formed on a projection screen through a fixed optical device. In contrast, there is an arbitrary number of pictures that can be created to represent that scene at that same point in time and viewpoint. As an analogy, one can think of the result produced by using an imaging device to capture the same scene multiple times without adjusting any of the device's parameters, in contrast to the result of an artist's multiple attempts to depict the given scene. We are not just dealing with the human inability to reproduce with the finest detail the same result, but mostly with the humane ingredients (i.e. emotion, cognition, communication, etc.) that influence the artist's intention and make the depiction unique by attaching aesthetic value.

A distinction that is made in this dissertation between images and pictures in the context of computer graphics is that the latter is not just a projection of 3D elements onto 2D by means of light interactions. It is not a mere storage area of numerical values. Making a picture implies that cognitive factors (e.g. attention, perception, recognition, comprehension, etc.) are accentuated during the process of image-making. Thus creating pictures with a computer becomes a complex task that requires to observe and replicate the methodology of humans; to take into account properties of visual perception and understand their connection to pictorial techniques. These are tasks that cannot be captured in a generally applicable mathematical formula.

This is a significant observation, since it allows us to extend the parametric space an image is formed within, to the multi-dimensional parameter space a picture is created in. The additional parameters may describe properties of the natural media to be used for the depiction, the characteristics of the surface that the picture is to be placed on or even a procedure by which the picture will be created. These additional parameters are almost always present when the image-maker intentionally interferes with the formation process of an image in order to turn it into a picture. Therefore, images can be considered as the basis for creating pictures, as long as a set of extra parameters is specified. Many artists unintentionally comply with this procedure of transforming real or fictitious spaces into pictures. For instance, painters of outdoors scenery create pictures by using not only their painting media and canvases as additional parameters to the visual image perceived through their eyes, but also their creativity and subjective perception. When dealing with imaginary compositions, the associations and interactions between the various parameters are much more complex. What is significant according to the distinction made here is that these compositions stemming from imagination will also result in pictures and not images.

Nevertheless, it is not up to the picture-maker to declare the outcome of his work as a picture or even further as artwork. It is the audience who subjectively will be able to interpret the visual representation and affirm whether it is a picture or art. It is thus interpretation of the stimuli arriving on the eyes rather than the retinal image formed on it, as John Ruskin argues: "You do not see *with* the lens of the eye. You see *through* that, and by means of that, but you see with the soul of the eye." [85, p.116].

One could consider that the picture-maker's function is to provide suggestions to the audience via the use of pictorial techniques. Equivalently, in computational visual sciences solving a mathematical formula, e.g. one that models purely physical interactions of light, does not imply an intent to create pictures, but images. Therefore an unintentional numerical error in the modeling of this process that scribbles artifacts into the computed image cannot be declared as an artistic process alone. An audience is required that will accept it as such. Similarly, when compressing an image for transmission it cannot be declared as artwork just because abstraction or stylization of image features takes place as a side effect of the intended purpose of the image transformation in the first place. The conversion of images into pictures can be done intentionally in order to become systematic, reproducible and carry the cognitive information across to the audience. Then these computational processes are elevated into picture-making tools or even pictorial techniques, rather than side effects.

1.1.2 Pictures Beyond Two Dimensions

An important property of pictures is not only the effective communication of spatial information between depicted scene objects, but also between the viewer and the scene. Pictorial depth is represented indirectly, since the surface carrying the picture is itself flat. True depth is not present in a two-dimensional representation, but it is inferred by the viewer himself using visual cues, known as depth cues. Centuries of artistic and scientific efforts to set rules, develop methods and procedures of creating pictures that appear three-dimensional have preceded the advent of computational methods that attempt it. In Medieval times, flatness dominated the depictive qualities of paintings, drawings, mosaics, etc. A thorough understanding of optics and visual perception was a rather obscure territory, but also cultural orientation favored other qualities in representations rather than spatial depth. For example, in the ancient Egyptian decorative artwork it was sufficient to depict significant events and particular features of the Pharaoh on his tomb rather than construct an accurate three-dimensional representation of his body. However, artists from the 15^{th} century and on, have systematically used their contemporary knowledge of picture formation and incrementally refined their skills to perfection. The masters of the Renaissance (e.g. Jan van Eyck, Tommaso Masaccio, Leonardo da Vinci, etc.) communicated the missing third dimension in their works by essentially using — and sometimes abusing — what in perceptual psychology is referred to as the monocular depth cues. The contemporary understanding of picture-making was elevated from being dominantly flat to increasingly being three-dimensional providing a sense of depth and volume.

Until the 19^{th} century, exploiting the monocular cues has been the standard method of creating pictures that communicate spatiality and in particular depth information. While there have been several inquiries throughout history in the facilities of the human visual system with regard to the perception of depth [118], it was Sir Charles Wheatstone, who for the first time [125] proved experimentally that our ocular disparity, and the differences in the two retinal images, are mainly responsible for the robust perception of depth when appropriate stimuli are provided. He furthermore constructed the first *stereoscope* in which he presented various stereoscopic drawings to demonstrate and prove his theory. He termed the mental ability to robustly perceive depth information from pairs of 2D stimuli *stereopsis*, after the combination of the greek *στερεό* (which means solid) and *όψη* (which means appearance). Simultaneously, the picture-making and viewing of such stimuli widely became known as *stereoscopy*.

The introduction of stereoscopy, in combination with the invention of the first chemical photographic processes, had an avalanche effect in the visual arts. Many have spoken about the demise of fine arts (i.e. painting). Nevertheless, the realism of photographs did not subvert the handcrafted appearance of artistic pictures. It actually functioned as a catalyst for the emergence of new artistic movements such as Surrealism, Cubism, Expressionism, etc., that followed. Artists shifted their interest in creating photorealistic artwork to more expressive techniques, using new methods and inventing new techniques. A limited number of artists in their search for a medium that can better communicate to the viewer depth and distances has experimented with, and even adopted, stereoscopy as one of their creative techniques.

There is no concise historical account of how widespread stereoscopy was in pictorial visual arts beyond photography, but a review and analysis of known artistic works that have been executed in the post-stereoscopic era reveals that certain difficulties arise with this peculiar medium. These are far from being associated with the creative capacity of the artists and, as the relevant analysis in a subsequent section shows, can be mapped and tackled through technical means, detached from the creative intention of the artist.

1.2 Motivation

Leonardo Da Vinci (1452-1519) notes in his "Treatise on Painting" [50, p.14]:

> *"A painting, though conducted with the greatest art and finished to the last perfection, both with regard to its contours, its lights, its shadows and its colors, can never show a relievo equal to that of the natural objects, unless these be viewed at a distance and with a single eye."*

With this note the Renaissance master embraces the desire of many artists throughout history, to invent, discover and practice these techniques of depiction that would allow them to stretch a picture beyond its two-dimensionality. It also demonstrates that the flatness of the pictorial medium, as well as its effects, was a well understood and appreciated limitation. It was this limitation that led the Renaissance artists to invest much of their creative and technical abilities into inventing or utilizing methods that replicate reality on the two-dimensional surface. The same limitation guided modern artists to utilize stereoscopic methods and this subsequently became a motive for pursuing in this work the design of methods by which stereoscopic artwork can be created using images in a computer. Therefore, this dissertation lays out fundamental ideas and algorithms supporting the thesis that *computer algorithms and methods can be devised to turn stereoscopic images into stereoscopic artistic-looking pictures.*

Even though many of the algorithms presented herewith are automated methods that build upon single view Non-Photorealistic Rendering (NPR) techniques, this work does not intend to compare the output of these algorithms to the artwork human artists can create. For the sake of simplicity, from hereon, when the words "artistic" or "art" are used to describe computer synthesized renditions, they should be considered to mean artistic-looking or resembling artwork. It is widely accepted by the scientific community that creating tools which allow non-artist end-users to generate handcrafted looking images with minor user intervention by no means equates to art, but may be useful in a number of different contexts. For example, the proposed algorithms could function as the basis for building advanced computer-based tools that can assist and complement artists in an interactive framework. They can potentially also be used by stereo photographers to transform their raw photographs into stereoscopic pictures (e.g. stereo paintings or line art), without the requirement of being skilled by hand themselves. Similar to the popularity single-view Non-Photorealistic Rendering algorithms currently enjoy among commercial software for image editing, video postprocessing, desktop publishing, etc., these proposed methods may have great utility in a stereoscopic context.

The main constraint set by the thesis is the requirement of augmenting *photographic images* rather than computer-generated images of 3D models. Thus it is appropriate to focus on the transformation of photographic input images acquired from imaging devices. The challenges faced in this work, as well as its goals, largely divert from existing 3D-based techniques that could be used to produce stereoscopic artwork, mainly because scene objects depicted in photographic images lack geometric descriptions, semantics and any other high level information. In contrast to these methods, such properties in this work have to be retrieved to some extent, using computer vision methods.

It is important to state that this work spans across different areas of research in computer science, but it is also tightly related and dependent on various disciplines of arts and psychology. The approach taken is to first identify how traditional artists have generated artistic stereoscopic imagery by hand; to identify their methods, requirements and limitations and use this knowledge to devise computer algorithms that can mimic artists or could assist them in the digital domain to achieve their goal.

1.3 Summary of Contributions

The main contribution of the work presented in this dissertation is the treatment of stereoscopy as an artistic medium within the scope of Non-Photorealistic Rendering research. Despite the fact that fine artists have utilized stereoscopy in order to enhance the depth perception of artworks, including painting, drawing and cartooning, to the author's best knowledge there has been no previous research that explicitly provided a thorough description of image-based computational methods that can be used to transform stereoscopic image pairs into stereoscopic pictures that resemble artwork. We outline in this dissertation a set of guidelines that form the framework over which a stereoscopic NPR pipeline has been designed and realized as a coherent software system. The usefulness of this approach, to identify problems arising due to the peculiarity of the medium itself and then solve them via computer algorithms, is demonstrated by the design and implementation of three different stereoscopic NPR algorithms: *stereoscopic drawing, painting and stylization.* These algorithms constitute novel ideas in the area of NPR and provide a stepping stone for further exploiting the potential of stereoscopy as an artistic medium. In addition, a set of stereoscopic interactive techniques is presented. These techniques enable the viewer to indirectly manipulate the stereoscopic space by altering the two stereoscopic images; they provide him with stereoscopic cursors that can assist him with viewing and perceiving depth of a stereo image pair and also they allow him to slice the generated stereoscopic artwork in order to observe the understructure of it.

Many image-based NPR works that have as a goal to create handcrafted looking pictures in computer science from a single view, take readily available knowledge from other disciplines and interpret or utilize it directly. In contrast, the thesis of this dissertation has required that research is first performed to collate material related to traditional stereoscopic artwork generation. Therefore, apart from the technical aspects of stereo artwork that may be useful to the computer scientist, in order for computer algorithms to be designed and implemented, historical information about handcrafted stereo artwork and artists that have been milestones to the evolution of the medium are presented. The collation of this non-technical material is further analyzed in order to expose knowledge that can be useful to other scientists who may set out to treat the subject from a different perspective or discipline.

1.4 Publications

The material presented in this dissertation has appeared in the following publications:

- Efstathios Stavrakis and Margrit Gelautz. Interactive Tools for Image-based Stereoscopic Artwork. *SPIE Stereoscopic Displays and Applications XIX, in San Jose, CA, USA, January 28–30*, Vol. 6803, 2008.

- Efstathios Stavrakis, Michael Bleyer, Danijela Markovic, and Margrit Gelautz. Image-based Stereoscopic Stylization. *IEEE International Conference on Image Processing 2005 (ICIP'05) in Genoa, Italy, September 11–14*, Vol. III, pp.5–8, 2005.

- Efstathios Stavrakis and Margrit Gelautz. Stereo Painting: Pleasing the Third Eye. *Journal of 3D Imaging, The Stereoscopic Society (UK)*, Issue 168, pp.20–23, Spring 2005.

- Efstathios Stavrakis and Margrit Gelautz. Computer Generated Stereoscopic Artwork. *1st Eurographics Workshop on Computational Aesthetics in Graphics, Visualization and Imaging (CAe'05) in Girona, Spain, May 18–20*, pp.143–149, 2005.

- Efstathios Stavrakis and Margrit Gelautz. Stereoscopic Painting with Varying Levels of Detail. *SPIE Stereoscopic Displays and Virtual Reality Systems XII, in San Jose, CA, USA, January 17–20*, Vol. 5664, pp.450–459, 2005.

- Margrit Gelautz, Efstathios Stavrakis, and Michael Bleyer. Stereo-based Image and Video Analysis for Multimedia Applications. *International Archives of Photogrammetry, Remote Sensing and Spatial Information Sciences (XXth ISPRS Congress) in Istanbul, Turkey, July 12–23*, Vol. 35, pp.998–1003, 2004.

- Efstathios Stavrakis and Margrit Gelautz. Image-based Stereoscopic Painterly Rendering. *Eurographics Symposium on Rendering (EGSR'04) in Norrkøping, Sweden, June 21–23*, pp.53–60, 2004.

1.5 Overview of Dissertation

This dissertation is progressively structured from the non-technical to the more rigorous scientific material. Chapter 2 outlines the principles of depth perception and stereoscopy. It discusses their connection to fine arts and documents the most important traditional stereoscopic artists and their works. This material sets the foundation for drawing important theoretical knowledge that is used in the subsequent chapters.

Chapter 3 reviews both computer vision and computer graphics literature that is relevant to the theoretical and practical aspects of this work. In Chapter 4, the framework for stereoscopic artistic rendering is described and the previously identified technical tasks that traditional artists have to carry out, are mapped and adapted from the analogue domain to the computational nature of the framework.

Chapters 5, 6 and 7 provide a thorough description of a set of novel stereoscopic NPR algorithms. These algorithms encompass many of the ideas discussed in the previous chapters. The generality of the framework is demonstrated by first presenting an algorithm that converts stereoscopic images into concept stereo drawings

(Chapter 5); then, an algorithm that generates stylized stereo image pairs that resemble stereo cartoons (Chapter 6) and, finally, a method to generate stereoscopic paintings (Chapter 7).

Chapter 8 proposes a set of human-computer interaction techniques that can be used to manipulate stereoscopic space and provides insight on how to integrate stereoscopic cursors. It also shows a method that can be used to interact with the understructure of stereoscopic artwork generated by our algorithms.

Chapter 9 concludes this work by providing a summary of the presented work and future directions that constitute potential topics for further research.

Chapter 2

Stereoscopy & Fine Arts

The process of creating pictorial representations usually involves an artist who uses an artistic medium (e.g. charcoal, color pencils, oil paints, etc.) to make marks on to a substrate (e.g. paper, canvas, etc.). Unlike three-dimensional arts (i.e. sculpting), when applying a 2D artistic medium on a 2D substrate the third dimension of the depicted 3D scene collapses on the substrate, and therefore works of painting or drawing can be primarily considered to be flat. Despite this fundamental limitation of pictorial media, the majority of such artworks manage to provide a sense of depth, even though it is not really present. To perceptually extend the picture beyond its flat material body, artists reinforce depth cues in the picture that provide the observer with information that can be used to infer the spatial properties of the scene.

In essence this is not different from the way we visually perceive depth and distances in our immediate environment. To construct the three-dimensional visual form of the optically perceived world, the human brain uses as input two images formed on our eye retinae. Thus it relies on the information present in these two 2D projections, referred to as the retinal images. The significant difference between the vivid three-dimensional world we are accustomed to naturally see and a painting or drawing is that the single three-dimensional world we perceive cannot be inferred only by the information present in the one retinal image, but requires both, something a single-view pictorial representation lacks. On the other hand, a painting will give an impression of depth, but in most cases the observer is not deceived into believing that the painting is a truly three-dimensional world and can easily distinguish it from such. Since our visual system in both cases (painted and real world) uses 2D projections, it becomes crucial to understand why this discrepancy arises between the real world and a depicted one.

The main reason lies in the ability of the visual system to use the dissimilarities of the two retinal images in order to disambiguate depth information. When looking at a three-dimensional scene, the two retinal images are spatially dissimilar and, in addition, there are points of the scene that one eye can see while the other one cannot, commonly referred to as occlusions. This parallax between scene points coupled with occlusions is exactly what provides the visual system with enough information to disambiguate depth and distances. The spatial disparity of a point between the two retinal images decreases as the point moves away from the observer. When looking at flat surfaces, such as pictorial representations, even though the two retinal images formed are dissimilar, they lack occlusions and the retinal disparities remain uniform across the surface. Therefore the visual system not only is not led to perceive true depth, but in contrast it can detect more easily the flatness of the medium.

Pictures may trigger controversial interpretations of depth perception and this has been used to create unfamiliar and thought-provoking artwork, as well as optical illusions. However, most artistic works usually are executed so that the viewer can establish a viewpoint to the artwork that enables him to become spatially related to it. But most importantly, artwork that intrinsically contains more than a single depth layer needs to communicate this information to the viewer, in order to be fully appreciated. Artworks lacking multiple depth layers and providing no means for the observer to spatially relate to them may shift to the realm of non-representational art; they may be perceived as incomprehensible, abstract or even fail to communicate effectively the third dimension. In this dissertation, such intentional interplay of depth perception with artistic expression will not be investigated. The main focus of our discussion will be on those works that actively employ traditional techniques in order to communicate depth information.

2.1 Depth Perception

The perception of depth and distances is triggered by a variety of discriminative stimuli. We are accustomed to process this visual information and subconsciously make estimates of relative and absolute distances. The information used by our visual system can be divided in two categories: *monocular* and *binocular depth cues*. The former can be perceived using only one eye, whilst the second category requires both eyes to be utilized. As Wheatstone demonstrated [125, 126], and subsequently various other researchers, binocular cues can be provided to the visual system by presenting each eye with a slightly different 2D image, similar to the ones formed on the retinae when looking at a real three-dimensional scene. These two images should allow the observer to replicate the geometric relationship that is established between himself and the various scene objects, as well as judge the relative positions of objects in space.

By utilizing the random-dot stereogram (RDS[1]), Julesz [54] provided evidence that even in the absence of other depth cues, binocular depth cues supply sufficient information for the perception of three-dimensional extents. Julesz was not the first to construct RDSs [52, p.547], although his research established the RDS as a major instrument for the study of many complex aspects of both the physiology of the eye and binocular vision. The random patterns visible in an RDS allowed Julesz and others to isolate binocular cues from other mechanisms of visual perception that give rise to depth and study them independently of monocular cues. Julesz's research is important because it provides experimental evidence that binocular depth cues, in close distances, are dominant and therefore exploiting them in traditional visual arts could serve well the purpose of communicating spatiality, for instance in a painting or a drawing.

Pictorial depth is perceived by the use of a subset of monocular depth cues that can be replicated within a picture. Durand [31] makes an extensive analysis of the limitations of the pictorial medium and proposes that limitations can be dealt either by eliminating them, compensating for them, or accentuating them. Durand points out that the strategy of *elimination* in order to deal with the flatness of the pictorial medium can be achieved by the reintroduction of the missing binocular cues through the use of stereoscopy. Even though a limited number of artists was aware of this strategy and exploited it, the main medium of communicating depth information in artistic works over the centuries has been the utilization of monocular cues. Thus we will summarize the monocular cues as these have been used by artists in the next section and then we will investigate the use of binocular stimuli in pictorial visual arts in the remainder of this chapter. For an exhaustive list of all sources of information for the perception of distance and relative depth, as well as pointers for specific analysis of each depth cue (in the context of vision science), interested readers should consult [51, p.5].

2.1.1 Monocular Depth Cues

The compositional elements making up a handcrafted picture usually carry a combination of several monocular depth cues. The depth cues commonly found in various

[1] A Random-Dot Stereogram (RDS) is a stereo pair of which the images are composed by randomly distributed dots. The images suggest no recognizable structure or objects when they are inspected monocularly. However, when these images are seen stereoscopically an underlying 3D structure emerges. The basic idea for creating an RDS is to shift the random dots only in one of the images to provide the necessary stereo disparity. An in-depth treatise of the RDS, its creation and its uses can be found in [55].

paintings, gravures, drawings, etc., are *linear perspective*, *size*, *occlusion*, *shades and shading*, *texture gradient* and *atmospheric perspective*. These cues are psychological and depend on our experience, cultural background and interaction with the environment. For depictions to be comprehensible, the audience must poses a cognitive understanding of the pictorial technique. Even though there are also two other monocular cues, *accommodation* and *motion parallax*, they are not replicated in static two-dimensional artwork. The former is an oculomotor cue that utilizes the adjustments of the muscles used to change the focal length of the eyes' lenses in order to focus at different distances. The second one sources from the motion of objects or the eye in regard to a point of fixation at a distance, e.g. moving objects with constant speed appear to move faster when they are located closer to the observer, than objects that are further away.

Size of the depicted objects allows a viewer to make subjective estimations of their distance. When an element is recognized, the familiar size of the object may be associated with the depicted one. For example in the painting shown in Figure 2.1(a), the woman is painted at a greater scale than the house and trees on the left, but is not perceived as being larger. Instead, the woman is perceived to be much closer to the observer than the house, which appears to be farther away. The reason is that our visual system is well accustomed to the sizes of the two forms and thus uses them to arrange the two forms in depth, together with other depth cues in the scene.

In addition, distance estimation can be performed when an assortment of the same, or similar, objects is depicted in a picture with different sizes. This size constancy cue can be clearly seen in the painting "Good Friends" of Ansdell Richard, Figure 2.1(b), where the flying birds are perceived to be of the same size and arranged along the depth axis of the painting, rather than considered to be a flock of birds of different sizes and all at the same distance.

Linear Perspective refers to the geometric relationships formed when points in space are projected through a 2D plane to the center of projection (i.e. the eye). If the perspective projection is accurate on the working surface of the artist, then the rays of light emanating from the picture to the eye of a viewer, being positioned at a specific location in regard to the artwork, could correlate the light rays of the actual scene and therefore the viewer would be able to perceive much of the spatial qualities of it. Nevertheless, as we will discuss later, monocular linear perspective is not sufficient for true depth perception, especially for objects at close distances. Perspective geometry has been known and utilized since the early Hellenistic times (4^{th}–1^{st} c. BC) [33, p.433], but it was systematized much later in the Renaissance

(a)

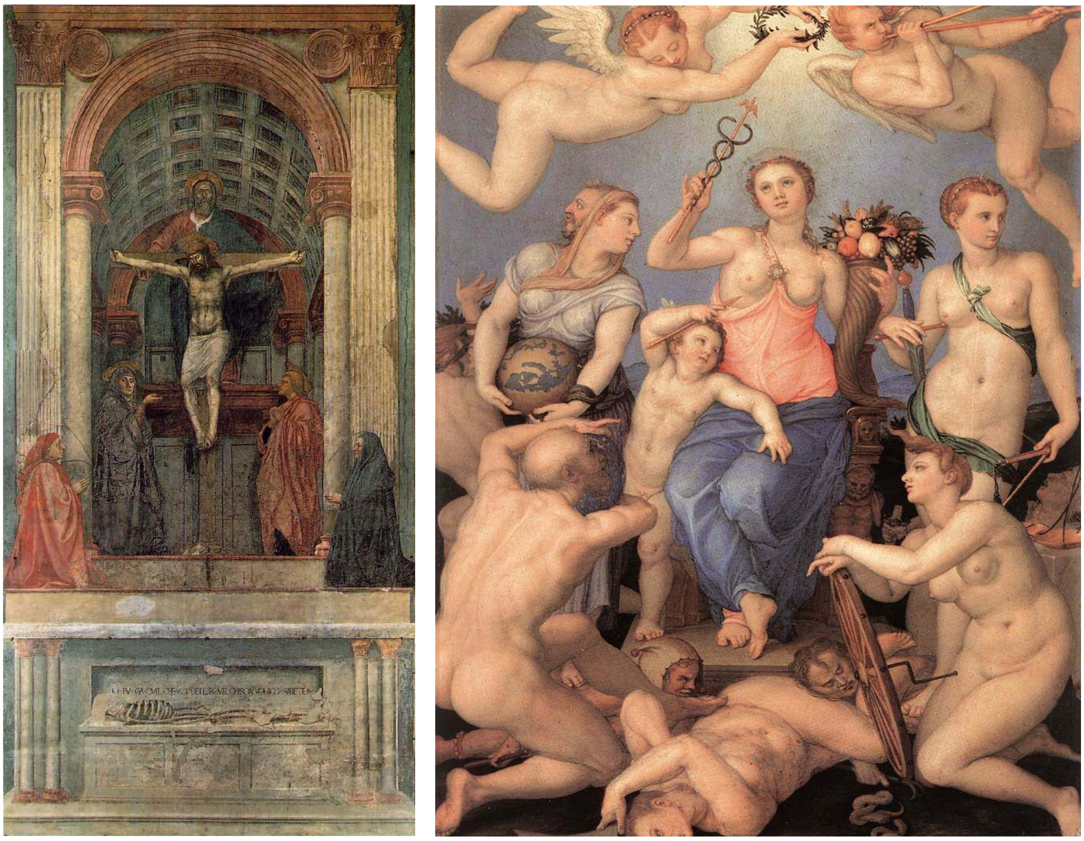
(b)

FIGURE 2.1 *(a) "Faraway Thoughts", oil on canvas (ca. 1880, 97.2 x 74.3 cm) by Ferdinand Heilbuth, (b) "Good Friends", oil on canvas (ca. 1856, 91.4 x 71.1 cm) by Richard Ansdell.*

(14^{th}–17^{th} c. AD) [34, p.52]. For instance, sculptor Filippo Brunelleschi is speculated to have assisted Masaccio in painting the "Trinity", shown in Figure 2.2(a), by sharing with him his knowledge of single-point perspective. The "Trinity" is considered one of the earliest paintings that demonstrates clear understanding and systematic use of linear perspective with a single vanishing point in the composition. According to an analysis of the painting performed recently by Talbot [114], the painting follows the rules of perspective so firmly that even fine details such as the nails in the hands of crucified Jesus are in fact perspectively correct.

Occlusion of objects is present on the majority of artwork. When two familiar surfaces are interpositioned in space, the silhouette of the foreground will partially occlude an element of the composition in the background. Objects in artwork may also be self-occluding, in which case portions of the same object obscure other parts of itself, which is very common in depictions of articulated figures (e.g. humans, animals). Occlusion strongly hints at the spatial arrangement of the occluding and the occluded objects or parts in three-dimensional space. Occlusion can give an indication of which object is closer, but does not by itself provide sufficient information on how far the objects are from the viewer or between themselves. In

Figure 2.2(b), Bronzino extensively uses occlusion, and self-occlusion, as a main instrument to communicate depth. The utility of interposition in this painting is clearly demonstrated by the lower part figures, whereas the two angels at the top of the composition, which are not occluded or occluding, are somewhat ambiguous in regard to the lower part of the composition. One cannot confidently identify whether the two flying figures are directly above, behind or in front of the figures of the rest of the painting.



(a) (b)

FIGURE 2.2 *(a) "Trinity", fresco (1425–28, 667 x 317 cm) by Masaccio, Santa Maria Novella, Florence, (b) "Allegory of Happiness", oil on copper (ca. 1564, 40 x 30 cm) by Agnolo Bronzino.*

Shading refers to the gradual changes of the color value of an object's surface, by adding black. Shading does not only give clues on the location of the objects in space, but it can also provide information about their curvature and orientation, thus making easier the geometric interpretation of the objects and the overall scene. There are various shading techniques, depending on the medium. For example in pen-and-ink illustrations, drawings, engravings and woodcuts, such as the one shown in Figure 2.3(a), hatching and cross-hatching are mainly used to produce shading effects, whilst in painting gradual addition of progressively darker pigments is applied.

The experimentation with shading sprang up various refined techniques of shading, such as chiaroscuro[2] and sfumato[3], used in the paintings shown in Figures 2.3(b) and 2.3(c) respectively. Furthermore, shadows cast from one surface to another are useful cues in identifying proximity between objects and are often executed by using shading techniques.

Texture Gradient can be seen when the depicted surface is not perpendicular to the line of eye sight or when it has curvature; then, naturally texture features become less distinct and foreshortened proportional to their distance from the viewpoint or they are distorted. Such an example of the use of texture gradient can be seen on the road made out of stones in the work of urban painter Caillebotte shown in Figure 2.4(a).

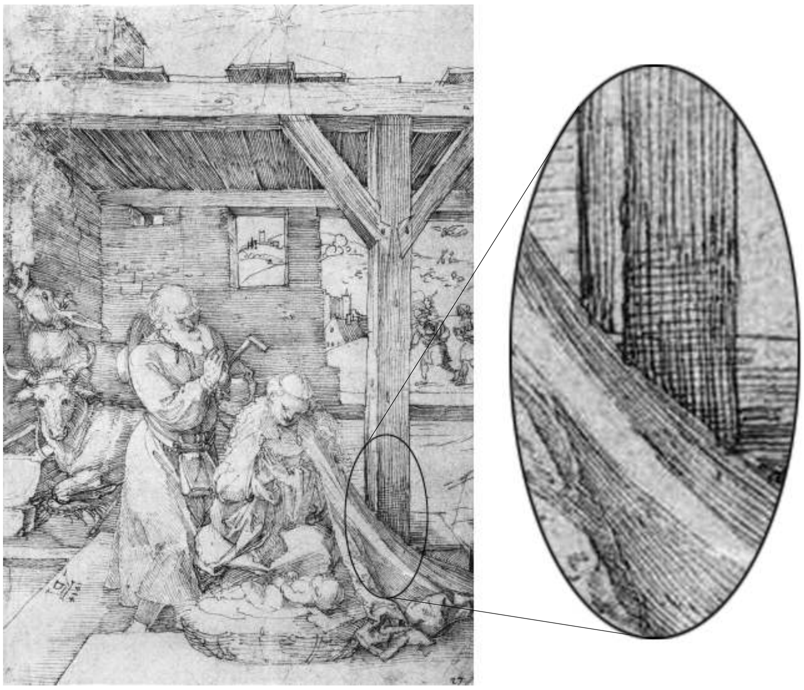
Atmospheric Perspective is observed when the visibility of distant elements of the scene is decreased by haze. In paintings this natural phenomenon is often replicated by using a bluish color in the respective colored areas and by decreasing the focus and contrast of the features that should appear at great distance. Atmospheric perspective has been widely employed in landscape painting, such as the one shown in Figure 2.4(b) by Flemish painter Wittel.

2.1.2 Binocular Depth Cues

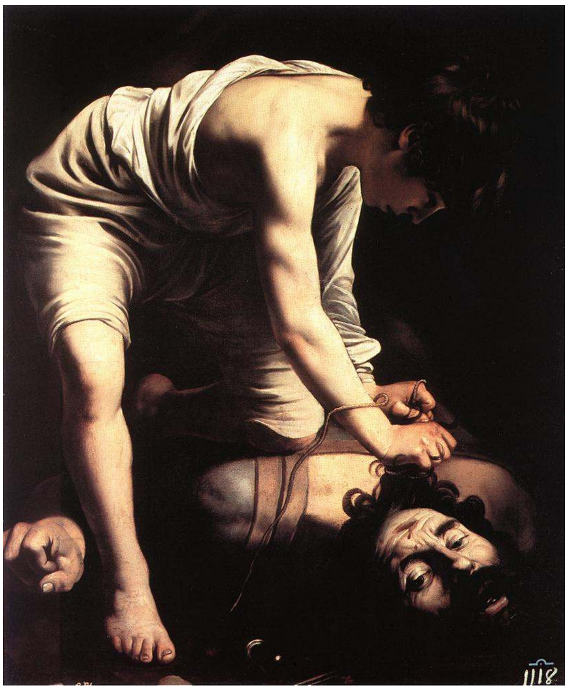
In close distances the perception of depth is greatly enhanced by the combination of information provided by both eyes. In pictorial representations these depth cues have been neglected by most artists, mainly because of the monoscopic nature of their work. The point of fixation of our eyes when looking at a picture always lies on the plane that equates the physical surface the picture was laid on. Thus across a picture, even if monocular cues suggest that elements are located at different distances from the viewer, the binocular facilities of the visual system contradict and counter these suggestions. By observation alone, it is easily verifiable that a large landscape painting produces a better sense of depth than one of objects that are nearby. The missing binocular depth cues, briefly described below, make it very unlikely for a painting of close objects to be mistaken as a real three-dimensional world, whereas a large landscape painting may give the illusion of a "window" to a distant 3D world. The two binocular depth cues, *vergence* and *binocular parallax*,

[2]Chiaroscuro means "light-dark" in Italian and is a technique used in pictorial arts to emphasize and dramatize certain objects of an artistic composition by using high contrast between light and dark.

[3]Sfumato is a technique used by artists to express a transitioning from light to shade within an object, leaving no noticeable contour [83]. Leonardo DaVinci describes the use of sfumato as painting "without lines or borders, in the manner of smoke or beyond the focus plane".



(a)



(b)

(c)

FIGURE 2.3 *(a) "The Nativity", pen on paper (ca. 1514, 31.3 x 21.7 cm) by Albrecht Dürer, (b) "David", oil on canvas (ca. 1600, 110 x 91 cm) by Caravaggio, (c) "Mona Lisa", oil on wood (77 x 53 cm) by Leonardo da Vinci.*

(a)

(b)

FIGURE 2.4 *(a) "Rue De Paris, Temps De Pluie", oil on canvas (ca. 1877, 212.2 x 276.2 cm) by Gustave Caillebotte, (b) "The St. Peter's in Rome", oil on canvas (ca. 1711, 57 x 11 cm) by Caspar Andriaans van Wittel.*

are very important in close distances and allow for less reliable depth estimates as the distance from the viewpoint increases.

Vergence of the eyes toward a point of interest in the visual field allows the human visual system, when estimating depth, to take into consideration the tension of the extraocular muscles that support the movement of the eyeballs. It has been experimentally found that convergence as a depth cue is less effective beyond 2 meters. It must be noted, however, that horizontal eye convergence can be voluntarily controlled, which, as we will discuss in the next section, is crucial for viewing stereoscopic pictures that provide the binocular depth cues.

Binocular disparity describes the differences between corresponding retinal projections of the same points in space. When the eyes fixate on objects, the point that the visual axes intersect lies on the surface of the object and its projection back to the retina is the same on both eyes. In this case we define horizontal disparity as being zero. The images of any points closer than the point of fixation are said to have negative disparities, whereas points beyond have positive disparities. Depth perception due to binocular disparity disappears at long distances from the eyes, since differences in the two retinal images are nearly absent.

2.2 Principles of Stereoscopy

Stereoscopic vision is the ability of the brain to combine the information from the two retinal images into a unified 3D percept. As Wheatstone has demonstrated with his mirror stereoscope [125] that when two pictures of the same scene, such as the ones shown in Figure 2.5, are created from horizontally disparate vantage points and then they are dichoptically presented to the eyes[4], the depth cues of convergence and binocular parallax are replicated. Note that even though binocular disparity is usually expressed in terms of the convergence angle, that is the angle (θ) formed at the intersection of the visual axes, shown in Figure 2.6, it is more intuitive to treat disparity as the displacement of points or features at the two projection planes.

2.2.1 Creating and Viewing Stereoscopic Content

The concept behind the generation of stereoscopic content is to depict a three-dimensional object on two surfaces, with correct proportions and horizontal disparities from two slightly displaced viewpoints. These two planes of projection can then be viewed stereoscopically, in which case the 2D points in the images are mentally

[4] When controlling the stimuli of each eye separately, then the stimuli arriving at each eye are said to be dichoptic [50, p.33].

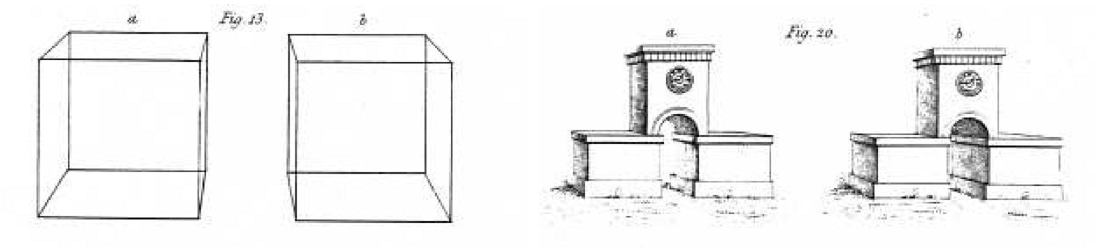


FIGURE 2.5 *Two of Wheatstone's stereoscopic drawings presented in [125].*

back-projected in space to provide a 3D percept. The key to viewing stereoscopic content is to successfully isolate and display separately each of these two projections to the human eyes.

The three types of disparity (i.e. zero, positive and negative disparities) must be encoded in the two views. When an object falls on the same points on each of the projection planes, the object will appear attached to the projection screen (S) when viewed stereoscopically, as shown in Figure 2.6(b). The projection screen is a plane where the two stereo projections are displayed on (e.g. a computer screen). Points that have negative disparities, as in Figure 2.6(a), will appear to float between the projection screen and the viewer, whereas any objects with positive disparities will appear to recede behind the projection screen, as shown in Figure 2.6(c).

The creation of stereo image pairs can be practically understood as a ray-casting process from a point in space back to the viewpoints. As the rays travel in three dimensions, they deposit marks on an intermediate and perpendicular to the median axis plane (plane of projection) for each of the viewpoints. This enables the use of imaging devices (e.g. analogue or digital cameras) and other planar surfaces (e.g. paper or glass) to take a snapshot of the light rays at any distance between the actual object and the viewpoint. When these two projections are then viewed stereoscopically, the light rays emitted from the images to the retina appear as if they were traveling from the actual object. Stereoscopic fusion of the two images by the brain can give an impressive sensation of three-dimensionality. The tremendous advantage of perceiving the 3D extents of a scene by only having two stereoscopic projections of it is that the physical objects are no longer necessary themselves; therefore it is possible to store, transmit, process or view the 3D scene from the viewpoint it was imaged or depicted by using only the two stereoscopic images.

When using imaging devices, a stereo rig can be formed by placing the devices in a binocular arrangement, similar to the human eyes' geometry. Errors in physical configuration of the stereo rig, as well as imperfections of the imaging devices themselves (e.g. internal imaging sensor misalignments), sometimes require that the

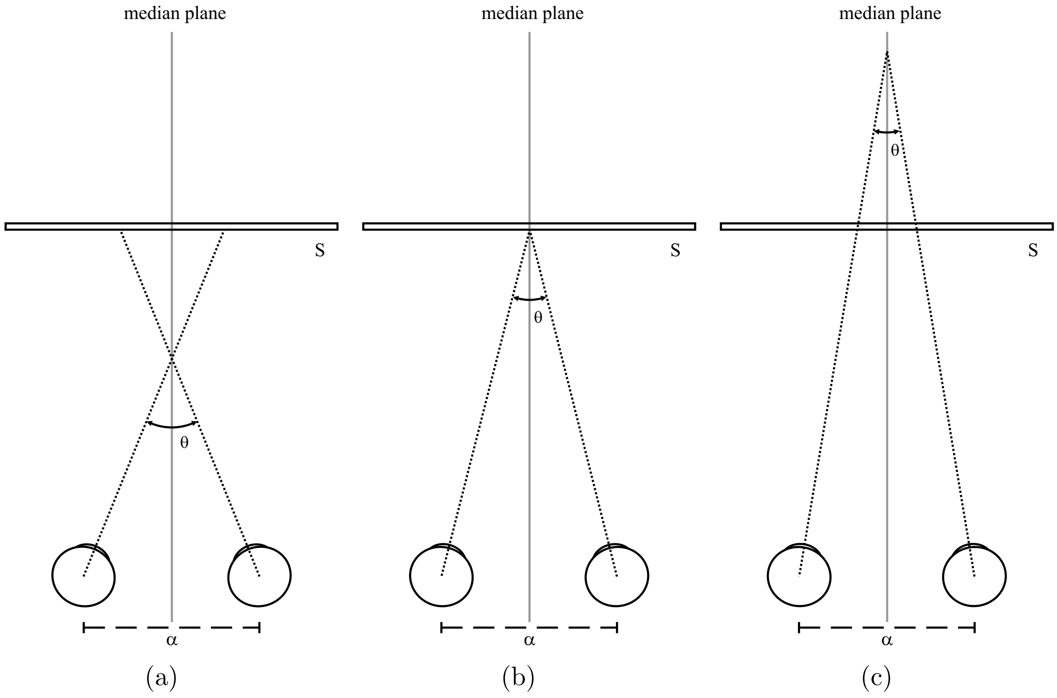
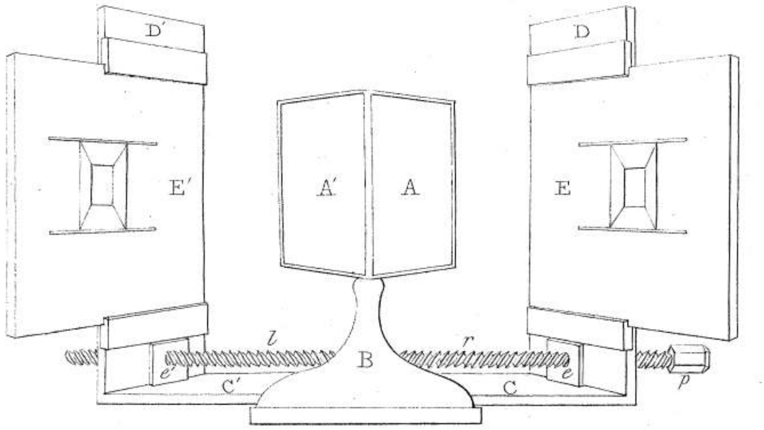


FIGURE 2.6 *(a) Negative disparity, (b) zero disparity, (c) positive disparity. In the illustrations shown here, α is the interocular distance, θ is the convergence angle and S is the projection plane.*

images are transformed, usually via calibration procedures, in order to counter these artifacts. It should be noted that it is possible to fuse stereoscopic images acquired by imperfect devices, without correcting their artifacts. This is because the human visual system can tolerate certain amounts of inaccuracies in the stereo images. However, when configuring cameras for stereoscopic image acquisition, it is recommended that the optical sensors' axes are set up to be parallel to each other and perpendicular to the scene. Optical axes that are not parallel (but in a so-called "toe-in" setup) imply that the sensors are not coplanar and thus vertical distortions are introduced in the stereo images. In addition, lens distortions should be minimized, as they also generate vertical parallax. This can be achieved by undistorting the image projections after calibration. Detailed analyses of these aberrations can be found in [129] and [124].

2.2.1.1 Stereo Viewing Techniques and Devices

Since the inception of stereoscopy a wide range of stereo viewing devices has emerged. Charles Wheatstone devised both mirror (shown in Figure 2.7(a)) and prism stereoscopes [118, p.301], which were succeeded by David Brewster's and later Oliver Wendell Holmes' more portable, lenticular stereoscopes, shown in Figures 2.7(b) and 2.7(c), respectively. The goal of all these devices was to assist their users in isolating the left and right views of a stereo pair to allow stereopsis. In contrast to Wheatstone's stereoscope, which was more difficult to construct, maintain and move, the handheld lenticular stereoscopes were vastly deployed for domestic use along with other "philosophical toys" [120] that were invented in the 19$^{\text{th}}$ century, such as the kaleidoscope and the zoetrope [101].



(a)

(b)

(c)

FIGURE 2.7 *(a) Wheatstone's mirror stereoscope adapted from [125], (b) Brewster-type lenticular stereoscope (Collection Early Visual Media – Thomas Weynants), (c) Holmes handheld stereoscope (Collection Early Visual Media – Thomas Weynants).*

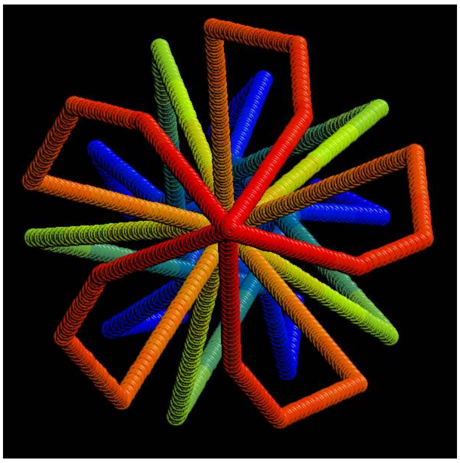
In the digital era a variety of devices and techniques have been developed for the presentation and viewing of stereoscopic content. These devices range from lightweight eyewear to head-mounted helmets and are sometimes coupled with supporting stereo projection technologies. The main advantage of digital stereoscopic technologies over the non-digital stereoscopes is that they can be used with computer-generated stereo pairs and therefore hardcopy printouts are not required. In addition they can be used to view stereoscopic videos and generally facilitate a wider range of possibilities via the use of emerging computer graphics and vision technologies. Popular manifestations of elaborate digital stereoscopy are those of Virtual and Augmented Reality.

Generally, a projection screen may be used to display the components of a stereo pair simultaneously (time-parallel) or in a sequence (time-multiplexed or field-sequential) [71]. All these methods on their basis are targeted toward optically separating the stereo components. In time-parallel stereo, both the left and right images are displayed simultaneously. The most popular stereo formats tailored for time-parallel display are the anaglyphic (mono- and poly-chromatic) and chromadepth. In anaglyphic monochromatic stereo, each component is rendered using a single color (e.g. red/green, red/blue or red/cyan). The separation of the two components is achieved via the use of color filters that the stereo pairs are being viewed through. Each of the filters eliminates the wavelength of the respective color for the corresponding eye, therefore one eye sees only one of the components. Polychromatic anaglyphic stereo, also known as the anachrome method, follows the same principles as monochromatic stereo; the main difference is that the coloring of the stereo components is done in full color, apart from the areas where differences occur, which are rendered in red and cyan. Example monochromatic and anachrome anaglyphs can be seen in Figures 2.8(a) and 2.8(b), respectively. The chromadepth method does not use two components in order to produce binocular disparity, but rather a color coding that when viewed through special chromadepth glasses produces parallax. A very popular chromadepth palette is that of a rainbow (red, orange, yellow, green, blue) on a black background, like in Figure 2.8(c). Blue should code the points that are perceived to be the furthest and red the closest ones, while the rest of the colors will be perceived as being at intermediate depth distances.

On the other hand, the time-multiplexed techniques require that the two stereo components are rapidly alternated on the display while the lenses of the eyewear used by the observer are shuttered in turns, so that one image can be seen from one eye at a time. The frequency of the lenses' shuttering is high enough that the brain perceives the stimuli dichoptically. Other technologies usually found on field-sequential stereo systems incorporate polarized light and respective polarized glasses instead of shutters. The polarized projection systems (e.g. a projector with polarized filters) produce light waves that vibrate in a single plane for each stereo component and can pass through only one of the polarized lenses of the eyewear used by the observer.

(a)

(b)



(c)

FIGURE 2.8 *Figure (a) shows an example monochromatic anaglyph (source: Wikimedia Commons (http://commons.wikimedia.org)). Figure (b) shows a stereo image that uses the anachrome method (source: Wikimedia Commons (http://commons.wikimedia.org)). Figure (c) is an image rendered using the ChromaDepth® technology (created with Gloodle by Impulse Inc. and wondertouch).*

2.2.1.2 Free-viewing

Binocular vergence of the eyes can be controlled in order to fixate at different distances, even when there is no target object at the point of fixation. The ability to voluntarily control the vergence of the eyes, called free-viewing or free-fusion, enables a viewer to optically isolate the left and right components of a stereo pair without the aid of any stereo viewing devices [51, p.7]. There are two types of stereoscopic free-viewing: parallel and crossed-eye free-viewing.

Parallel free-viewing occurs when the eyes diverge so that the axes of sight are parallel, which is the natural state when viewing objects at very long distances. If small stereoscopic pairs of which the width does not exceed twice the amount of interocular distance (approx. 12 cm), are viewed side-by-side and at a distance of around 20 cm in front of the eyes, while they are in parallel free-viewing state, then stereopsis can be achieved. Parallel viewing requires that the left image is on the side of the left eye and, respectively, the right image on the side of the right eye, as shown in Figure 2.10(a). The easiest way to achieve voluntarily parallel viewing is to fixate at a far object and bring into the visual field at a distance of 15 cm a stereo pair designed for parallel viewing (e.g. the pair shown in Figure 2.9). Parallel viewing cannot be used to fuse distant or large stereo pairs and therefore its utility is of limited interest, especially for works of art that are usually much wider.

Crossed-eye free-viewing is a more appropriate method for fusing larger stereoscopic images freely. In this mode the images of the stereo pair are swapped, with the left image being on the side of the right eye and the right image on the side of the left eye, as shown in Figure 2.10(b). The procedure can be performed by using the stereo pair shown in Figure 2.9:

> "Position the stereo pair perpendicular to the visual direction at a distance of 40 cm from the eyes, then bring into the visual field and fixate at the tip of a thin object (e.g. a pen or the forefinger) positioned at a distance of 20 cm from the nose. Slowly remove the aid while the eyes are kept converged at the initially fixated point. If the procedure succeeds, the stereo pair should appear fused.
>
> Once the procedure is learned, it is trivial to cross the eyes and adjust their fixation point for both small and large stereo pairs, even at great distances. When free-viewing, the fused stereo image appears between the two stereo components that are still visible. The two components can be temporarily removed from the visual field by bringing two planar objects in front of each eye so that they are perpendicular to the median plane. By eliminating the individual components, the fused image can be

perceived alone. Once crossed-eye free-viewing is mastered, it becomes another mode of seeing that one can switch to at will, enabling the fusion of stereo pairs within seconds." (see also [36])

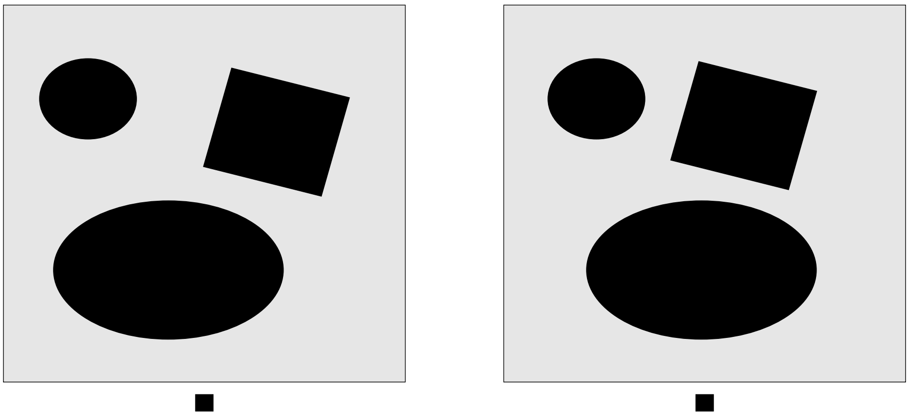


FIGURE 2.9 *An example stereo pair with simple geometric shapes. Clearly it is difficult to identify the position in space of the different shapes, since there are not sufficient depth cues. When the stereo pair is viewed using parallel free-viewing, it immediately becomes apparent that the square is closer to the viewer, the large ellipse is further back and the small ellipse is between them. The stereo pair can also be seen using crossed-eye free-viewing, in which case space inverts, so that the large ellipse appears closer to the viewer, the square further and the small ellipse again between them.*

2.2.2 Binocular Rivalry

When the two components of a stereo pair are different enough to prevent binocular stereopsis to take place, then the stimuli are said to produce binocular rivalry [3]. The main types of binocular rivalry are *contour* and *color rivalry*. The former describe the phenomenon produced by stereo pairs that have significantly different contours, while the latter exhibit large deviations in coloration of features that should otherwise be corresponding. When binocular rivalry occurs, the percept from only a single eye is consciously visible at a time. Usually perception alternates between the images of each eye, or one of the images becomes dominant suppressing the other; in either case without perception being brought to a state of stereopsis. In practice, extended exposure of the visual system to rivalrous stimuli causes discomfort and in stereoscopic picture-making it should be avoided.

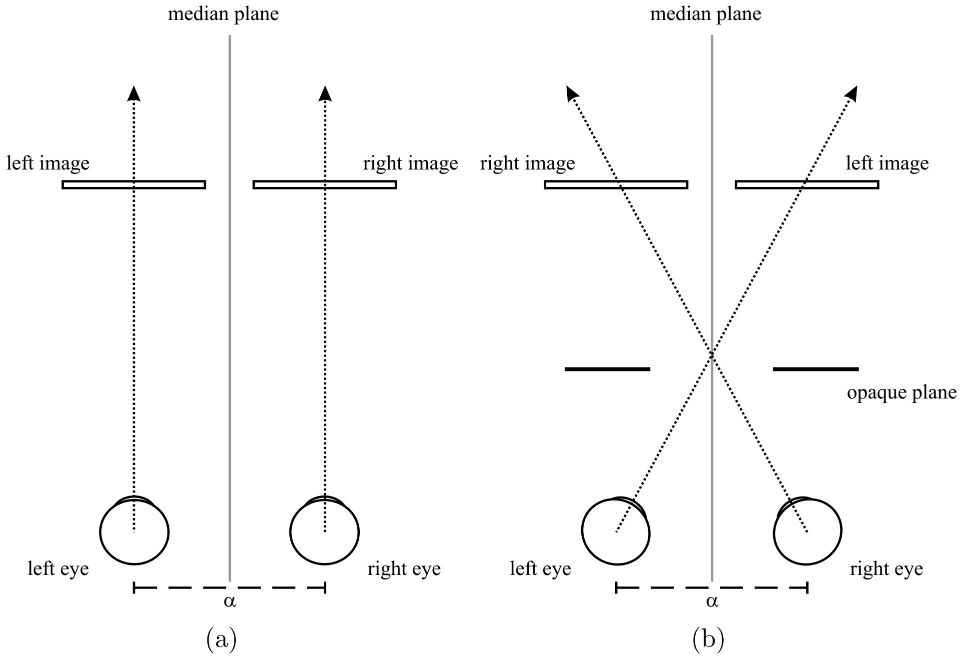


FIGURE 2.10 *(a) Parallel free-viewing, (b) crossed-eye free-viewing.*

2.3 Stereoscopy in Fine Arts

The importance of Wheatstone's discovery was not only the fact that he drew a new path for studying binocular and depth perception; a more subtle, yet important side-effect of his inquiry into visual perception was that he invented a new way of creating pictures. It is well known that Wheatstone was not the first one to investigate binocular vision and create dichoptic stimuli and viewing devices [52, p.62], [118]. The art of stereoscopic picture-making was vastly exploited in conjunction with photography that was invented very shortly after stereoscopy. The two techniques became extremely popular in the second half of the 19th century, but traditional artists like painters did not create stereoscopic artworks until later in the 20th century.

There have been several books and long-standing journals that expose the stereo photographic process, but very scarce is the availability of texts documenting handcrafted stereoscopy, beyond the use of imaging devices. We investigate here the impact that stereoscopy had in arts and provide an initial account of important handcrafted stereo artworks together with an investigation into the techniques used; not only for historical purposes but mainly because our algorithmic work, presented later, draws knowledge from the principles, methods and problems initially concerning stereo artists in order to provide computational equivalents for the digital era.

2.3.1 Stereoscopic Artwork

A stereoscopic piece of art is composed by two components, which can be thought of as the simulation of each of the retinal images of the artist's, or viewer's, eyes. This two-viewpoint depiction can be considered as an uncoupling of a real or illusionary 3D composition space into a stereo pair of projections. This means that the dual artwork may be either an artist's depiction of reality, directly as it is seen and subsequently transferred to a pictorial working surface, or an artistic composition from the artist's imagination.

Each of the two finished pictures can perfectly stand as an artistic piece of work separately. However, there is a distinct advantage: viewing the artwork stereoscopically, with the 'third eye', the spectator can see inside the artist's composition space and observe the peculiar three-dimensional world made out of artistic media, which cannot be perceived in either of the stereo components alone. But it is not simply an accurate communication of three-dimensionality that makes stereo art interesting. When artwork is executed and viewed stereoscopically, depicted objects can freely detach from the pictorial surface and protrude toward the observer or recede behind the surface they have been laid on, immediately exposing an immersive space that exists perceptually in the brain; the observer does not have to imagine and assign spatial relationships to the 2D picture, but can directly see what the artist was intended to present him with.

Stereo artwork should be considered as a well defined technique for an artist to intentionally engage his viewer into spatial aesthetics, rather than a limiting factor for the viewer's imagination. Stereoscopy can function as an artistic medium that *clarifies space* and *improves the perception of spatiality.* When the intention of the artist is to allow subjective interpretation by providing ambiguous depth cues, there are long standing monoscopic techniques to achieve it. Actually, the masterful creation and manipulation of stereoscopic spaces enabled artists to produce interesting spatial effects that were not possible in single-view artwork.

A rather obscure advantage of stereoscopic artworks over other media lies beneath the obvious communication of depth. When viewing stereoscopically, it is not possible for the observer to divert his attention out of the stereoscopic space. While the viewer is looking at the two components of a stereo piece, the real world itself defocuses and is superseded by the stereoscopically fused artwork. This side-effect of absorbing the viewers' visual attention within the artwork is an effect many artists would be pleased with, if achieved under any circumstances. In stereoscopic arts, it becomes a requirement to engage visually with the artwork in order to perceive its extent, opening a direct channel of communication between artist and observer.

2.3.2 Timeline of Stereoscopic Artworks

Artists, being creative individuals, tend to experiment with different tools and apply, combine and exploit various techniques in their work. Even though less widely known, stereoscopic handcrafted paintings and drawings were executed as early as the time of inception of stereoscopy.

Dual pre-stereoscopic drawings have been created by various early visual perception researchers and artists, but it is nowadays widely accepted that these scientists and artists did not have a clear understanding of the facility of the visual system, formally to be termed by Wheatstone as stereopsis. This limits the usefulness of these pseudo-stereoscopic pictures for us, since an understanding and intention of manipulating stereoscopic space must have also been absent. For example, several pre- and post-Wheatstonian drawings that have two components and appear to be stereoscopic are considered to be a duplication of the same artwork or merely accidental. The most famous such artwork that raised a lot of controversy and has led many scholars, even today, to erroneously doubt the originality of Wheatstone's discovery are the Chimenti drawings [119], shown in Figure 2.11.

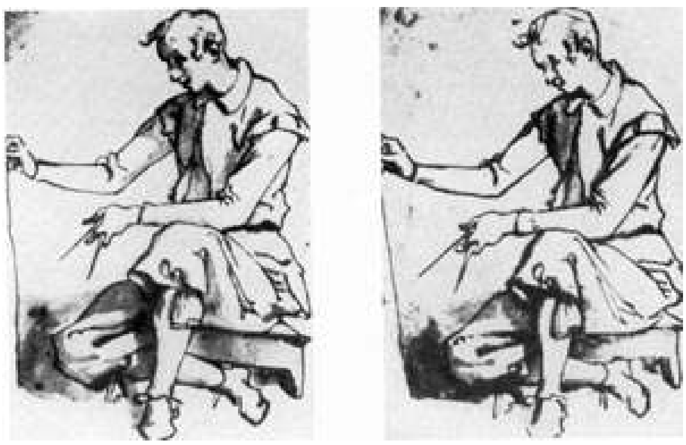


FIGURE 2.11 *Two drawings by Jacopo Chimenti (1554–1640) that have sparked great controversy about Wheatstone's priority in discovering stereoscopy. The drawings have been thoroughly studied and it is accepted that the stereoscopic depth is largely inconsistent and accidental.*

Investigating from the inception of stereoscopy and on, several stereoscopic drawings can be found within most early technical articles about stereoscopy, with that of Wheatstone being the first, but mainly for the purpose of illustration and idea communication rather than artistic composition. It is very important to consider that photography was not yet invented at that time, therefore picture-making was mostly performed by hand. Nevertheless, it is still not trivial to uncover artists that have consciously used stereoscopy. For example René Magritte (1898–1967) appears to have executed multiple early quasi-stereoscopic paintings, but did not further exploit the possibilities. Magritte's compositions have very small parallaxes, which could be considered purely accidental. Many of his works feature a subject that is dual and can be fused, but the background usually produces strong binocular rivalry. One of his quasi-stereopaintings that seems to work well is "L'Homme au Journal" (1928), shown in Figure 2.12. According to information by Sylvester and Whitfield [112], Magritte did not record any of his works as being stereoscopic[5].

In the middle of the 20th century, painters technically aware of the effects of binocular vision in the human visual system have undertaken the tedious task of painting two stereoscopic canvases instead of one.

Oskar Fischinger (1900–1967), a renowned experimental filmmaker and artist, has produced some stereoscopic paintings, mainly abstract compositions of geometric shapes, such as the "Circles in Circle" (1949), "Triangular Planes" (1949) and "Distant Rectangular Forms" (1951)[6]. Most of the shapes in the first two abovementioned paintings of Fischinger have a gradual depth arrangement which is pleasing when viewed stereoscopically, however there are areas in them that are very difficult to fuse. On the first painting the lower rectangle and circle have an enormous disparity, whereas in the second painting the orientation of the red and blue triangles, on the top left, make stereoscopic viewing of the artwork particularly challenging. On "Distant Rectangular Forms" Fischinger painted masterfully a mosaic of colored rectangles that provide a unique sensation of depth.

Fischinger did not limit his stereoscopic experiments to stereo painting only. After 4 years of experimentation with the stereoscopic medium in 1952, he created a stereoscopic animation, dubbed "Stereo Film". The process of making "Stereo Film" involved the painting and shooting of brush strokes progressively. According to Moritz [74, p.135], "Stereo Film" was created as a test to show that Fischinger could compose abstract animations in 3D, but his proposal for a full length "Stereo Motion Painting" was unfortunately not funded and was subsequently abandoned. This stereo test was screened a few times together with stereoscopic works by Hy Hirsh, Dwinell Grant, Norman McLaren and Harry Smith [74, p.236].

At the same time Fischinger has been experimenting with stereoscopy, illustrator Lee Allen published a paper [4] describing in much detail the process of cre-

[5] The author has inspected photographs of various paintings by Magritte and found that "L'imprudent" (1927), "Le point de vue" (1927), "La pose enchantée" (1927) and "L'Homme au Journal" (1928) have the best stereoscopic characteristics, the others either feature no disparities or cannot be seen in stereo due to binocular rivalry. The author would like to thank Jan Bron of the Magritte Museum for the short correspondence regarding Magritte's quasi-stereoscopic works.

[6] The author wishes to thank Mrs. Cindy Keefer of the Centre for Visual Music (Los Angeles, US) for providing the assigned names of these paintings.

FIGURE 2.12 *"L'Homme au Journal" (ca. 1928, 116 x 81 cm) by René Magritte / ©VBK, Vienna, 2006 (used by permission).*

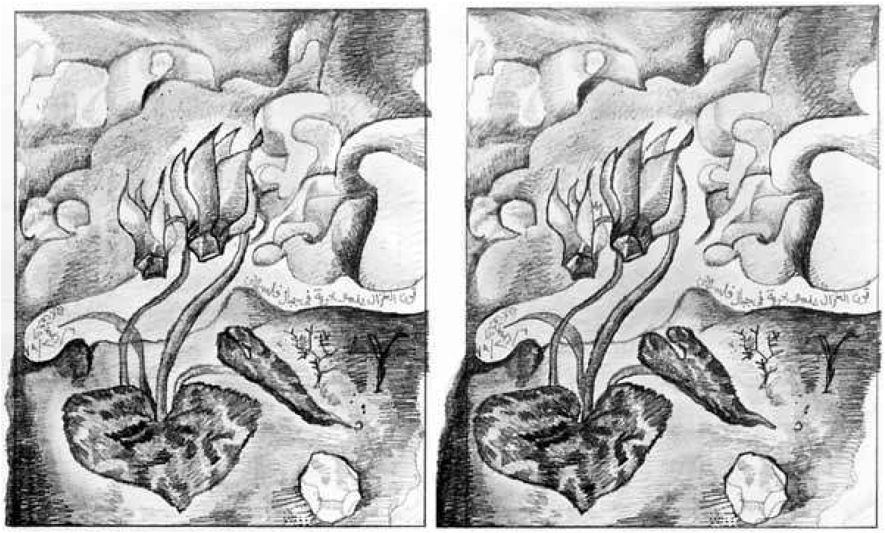
ating stereoscopic drawings and illustrations. The work of Allen is very thorough and gives insight on the process of creating manually medical stereoscopic illustrations. He explains how angular perspective can be used in stereoscopic drawings and clarifies that the correct way to proceed with a stereoscopic drawing is to preserve the relationship between the point of view and guiding marks (e.g. vanishing point) made on the drawing surface, while laterally displacing the subject within the layout to view it from two different angles. He also discusses the combination of stereo photographs and drawing and states in his paper: *"Stereograms produced by a combination of drawing and photography can solve certain pictorial problems more easily or better than either medium alone."* His knowledge of the medium is so elaborate that he describes a method of drawing stereoscopically a real human brain by using multiple dissections, cats' eyes using radiographs as a reference and various other complex subjects. He further describes the construction of a drawing board specifically tailored for stereoscopic work.

Nevertheless, Allen's stereo drawing board would appear simplistic compared to devices invented by various scientists and artists specifically geared toward creating 3D pictures. For instance, Prof. John T. Rule of MIT has submitted a patent application in 1937, which he was awarded later in 1939 in the US, describing in great detail an instrument for stereoscopic drawing [84]. His apparatus is composed by a drawing board, a pencil that can be adjusted in space, a binocular viewer and other supporting mechanical parts. Similarly, Cook submitted a patent application for a different, but impractically complex, stereoscopic drawing apparatus in 1953, which was awarded to him in 1958 [22]. A more compact and accurate instrument was invented independently by Palestinian artist and scientist Vladimir Tamari in 1963. Tamari's invention is notable not only because of the mechanical superiority it features over previous devices, but also because the inventor himself as an artist has produced hundreds of artistic stereoscopic drawings while using it; for an example see Figure 2.13(a). Tamari's 3 Dimensional Drawing (3DD) instrument, shown in Figure 2.13(b), has been featured in multiple publications with central focus on stereoscopy and he has written various articles about its construction, as well as its use for artistic purposes [115].

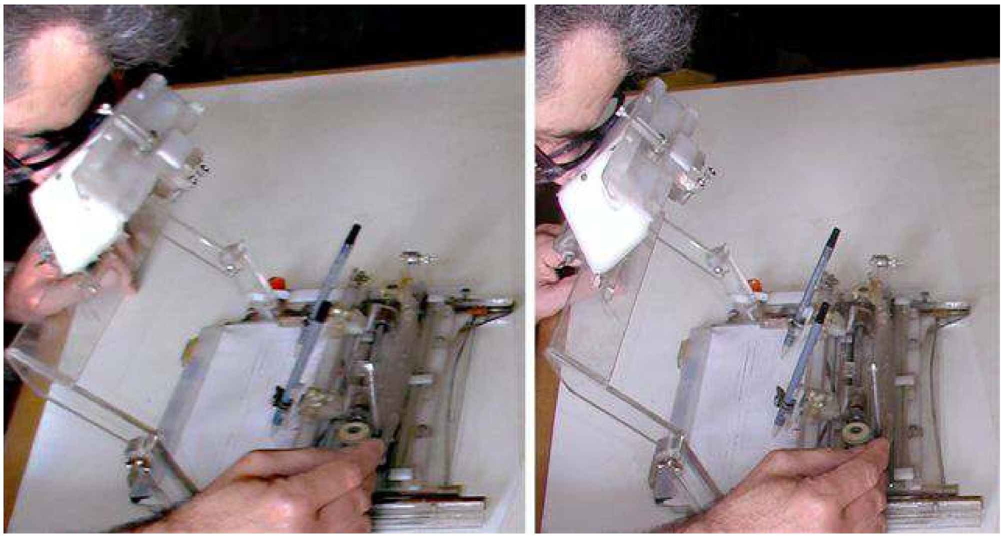
In the same line of work in stereoscopic drawing, but much later, Arthur Girling has published a book [37] that explains methods for creating stereoscopic drawings by hand. The book is more of a hands-on guide and it cannot be directly derived whether the author was aware of the work of Lee Allen and others, neither does he provide any relevant bibliographic references to older stereoscopic artworks. However, his methods are easy to follow and his book has some thought-provoking well-illustrated text and many stereoscopic drawings.

At the beginning of the 1970s, Alphons Schilling, Salvador Dalí (1904–89), Roger Ferragallo, Michael Kupka and Heinz Günther Leitner almost concurrently created stereo paintings and drawings proving that even though handcrafted stereoscopic content is particularly demanding in artistic and technical capacity, it can be used purely as an artistic medium beyond its obvious utility in sciences.

Alphons Schilling has executed a multitude of stereoscopic compositions that are both dual- and single-component. Schilling has built various viewing devices, the *Sehmaschinen*, that allowed him to take stereo artwork a step further and generate not only dual component works, but also single component canvases. The former are both compositions using paints on canvas, but also various black and white pieces that have the appearance of random-dot stereograms (e.g. revealing shapes of human bodies in various postures). The single component paintings are compositions of gradient patterns in which, according to Schilling himself, lines define planes that when viewed with both eyes open and a single prismatic lens in front of the one eye only, a pleasing sensation of gradual depth can be perceived. Other notable achievements of Schilling include the installation of a massive stereoscope in Helen Hayes Hospital on Hudson River (New York, 1983), his pseudoscopes that invert



(a)



(b)

FIGURE 2.13 *Figure (a) shows a stereoscopic drawing, "Cyclamens Grow Freely in the Hills of Palestine", pencil on paper (1979) by Vladimir Tamari. Figure (b) shows Tamari's 3DD stereoscopic drawing instrument [115], built in 1982 (2004) (images used by permission).*

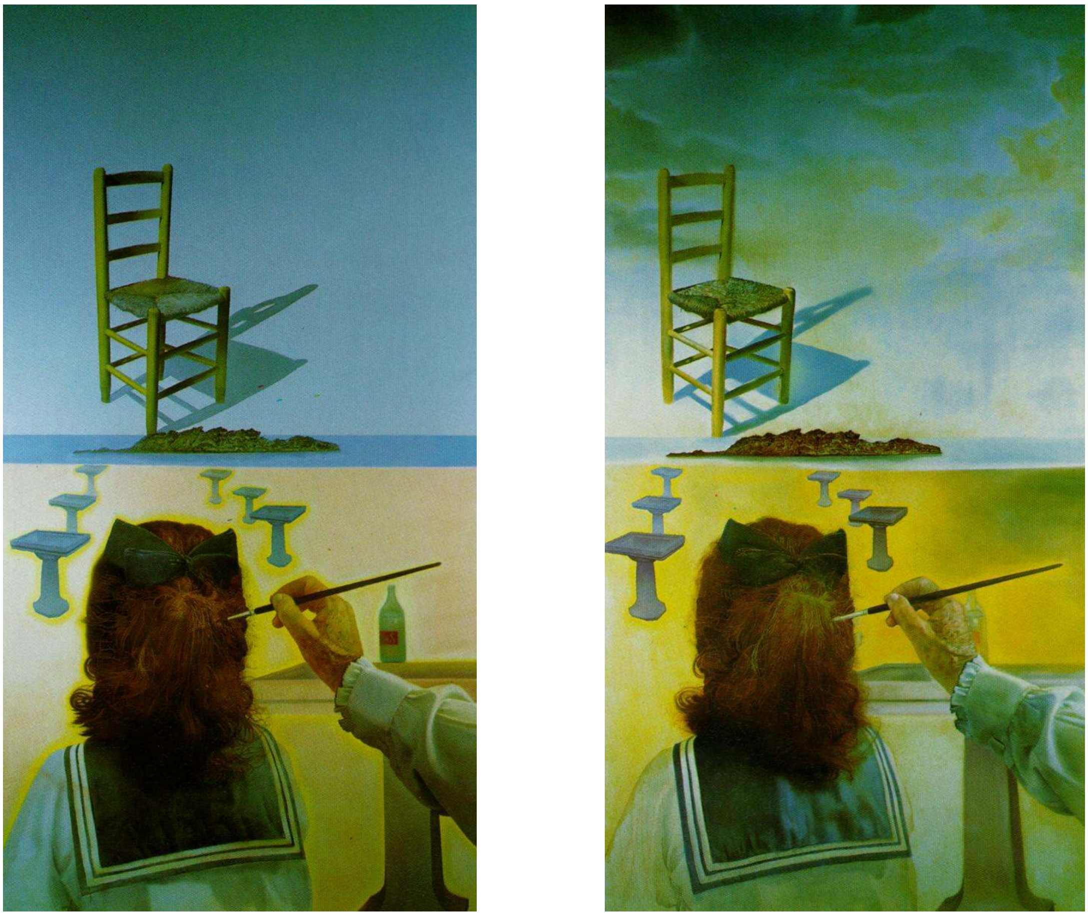
space and a head-mounted device, called "Video-Head-Set" (1973), that is similar to the "Ultimate Display" described and later constructed by Ivan Sutherland [111]. Schilling's works are still exhibited around the world and it is typical to find various types of custom stereo viewers installed in the exhibition spaces, allowing the visitors to see the 3D worlds emerging from his canvases.

Salvador Dalí has worked with holography as well as stereoscopy. According to Robert Descharnes[7], Dalí was studying stereoscopy since 1961 and Descharnes has assisted him with various issues arising on his initial experiments. As Descharnes writes, *"The extreme precision with which he paints his subjects, copied according to his needs just as expertly from photographs as from nature — his talent allows this — makes him define painting in this way."* Descharnes also reveals: *"All the painter's work turned toward the study of the variations of colors, values, and the rendering of the lights and shadows from the canvas to the other in order to achieve a three-dimensional effect and to offer a new stereoscopic, binocular vision, thanks to the optical superimposing of his two paintings."* Descharnes refers to binocular color mixing usually producing optically blended colors that can only be observed in stereo. For example, in his painting "The Sleeping Smoker" Dalí uses color variations across the two components that produce a strong glossy yellow when viewed stereoscopically[8]. Milder color variations across the two stereo components, particularly on shading rather than hue, seen in other works of the painter do not produce gloss, but instead enhance the vividness of the subjects and increase the plasticity of the objects in the stereoscopic space. Various stereoscopic paintings are exhibited in the Dalí Theatre-Museum of Figueres in Girona, Spain. Remarkable is his massive stereo painting "The Chair", shown in Figure 2.14.

Dalí was not the only one to experiment with binocular color mixing in his stereoscopic paintings. Roger Ferragallo has extensively employed this perceptual phenomenon in many of his works, such as "Stellations No .1" (1972) and "Homage to Albers" (1972) (see Figures 2.15(a) and 2.15(c)), to achieve a playful interaction of color perception in stereo. The work of Ferragallo with colors in stereo is very thorough and his method for creating "Stellations No. 1" is rather intriguing: *"I employed the optical mixture of colored dots by treating the left or right image of a dot pair with a different hue, value or chroma. Some of the dot pairs were painted exactly the same; some were painted using phosphorescent powders suspended in an acrylic medium. The combined effect of pairs that are optically mixed and those*

[7]Robert Descharnes was a friend and collaborator of Dalí. He is considered a Dalí expert and has written numerous books about the master.

[8]The optical color mixing of rivalrous color hues produces a percept that is usually referred to as *binocular lustre*.



(a) (b)

FIGURE 2.14 *"The Chair", oil on canvas (ca. 1975, 400 x 210 cm), (a) right component (b) left component, by Salvador Dalí / ©VBK, Vienna, 2006 (used by permission).*

that are not gives the striking impression that the points are (atmospherically) giving off both direct and reflected light." [36]. Ferragallo also experimented with the inversion of space in his painting "Transpositions" (1972), shown in Figure 2.15(b). His involvement in the development of stereoscopic techniques in arts resulted in many works, which range from dozens of drawings, see examples in Figures 2.15(d) and 2.15(e), to multiple large color canvases and even a massive mural ("Apollo Mandalla" (1972)). He has also made additional effort to document his techniques on the subject and has published a manifesto [36] in which he calls the artists' community to reinstate stereoscopy in their works and advance their knowledge in stereoscopic aesthetics.

Like other early stereo artists, Michael Kupka experimented with the conversion of stereoscopic photographs to what he calls StereoView painting and drawing, without the use of a computer. He further invented and explored the StereOil painting and drawing techniques. StereOil works are created by combining the left and right stereoscopic paintings or drawings directly on a single canvas.

Many of the known stereoscopic works are compositions of geometric shapes in abstract spaces, typically based on concept stereo drawings that are constructed carefully by the artist. However, it is also known that some artists (e.g. Dalí) have used stereoscopic photographs as a reference. We could therefore divide stereoscopic works into photographically and non-photographically assisted. The former usually present real objects and more complex shapes and are rather hard to construct without reference or a mechanical device (e.g. Tamari's 3DD), while the latter are easier to create since they feature relatively simpler objects to draw in stereo, but allow artists to communicate imaginary spaces that have very strong and engaging depth extent. The use of photographs as a reference by artists is rather important, because it motivates the mapping of this process into a computational framework that uses photographic images to create stereoscopic pictures, which is not a trivial task with existing technologies.

2.3.3 Drawbacks of the Stereoscopic Medium

When reviewing the above sections discussing depth perception, stereoscopy and stereoscopic artwork, it is not directly obvious why stereoscopy did not spread among artists, but in contrast became a lesser known and utilized technique. There are various reasons for this that are related mostly to stereoscopy itself, but also to social and artistic trends.

The technicalities involved in stereoscopy can be divided into those related to the artist and those relevant to the audience. The artist is required to acquire a sig-

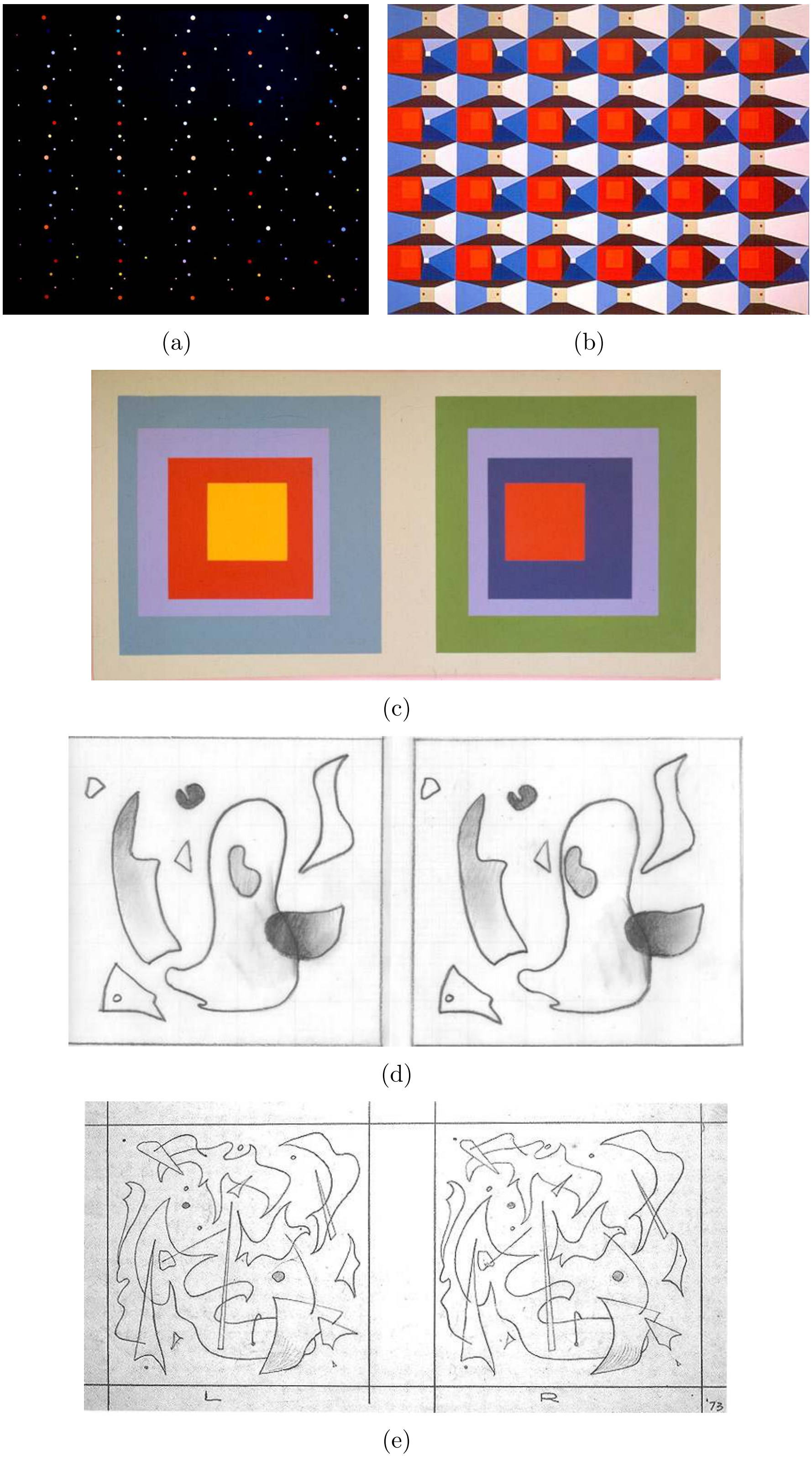


FIGURE 2.15 *(a) "Stellations No. 1", acrylic (1970, 183 x 213 cm), (b) "Transpositions", acrylic on canvas (1972, 91.5 x 122 cm), (c) "Homage to Albers", acrylic (1972, 61 x 122 cm), (d) "Amoeboid planes in space", pencil on paper (1966), (e) "Flight", pencil on paper (1973), concept drawing for a painting. All artwork by Roger Ferragallo, appropriate for crossed-eye free-viewing. (All images used by permission.)*

nificant amount of technical knowledge about the human visual system, the creation of stereoscopic stimuli and the constraints within which they become effective for their audience. Manipulating spatial properties of the artwork by shifting between stereoscopic and normal vision while working constitutes one of the less critical, yet important, limitations. In practice the artist, for a single work, will alternate his vision between the two viewing modes multiple times to ensure that the artwork develops as desired regarding the stereoscopic properties of it. Using photographs as a reference and further creating accurate stereoscopic drawings to preserve disparities is not sufficient, since coloration has to also be stereoscopically correct. Particularly challenging are fluid pigments that, when overlaid, they may blend to produce undesired inconsistencies.

Looking at stereo artwork creation from a purely practical viewpoint, an artist is required to work at least twice as much as he would for an equivalent single component piece. The complexity of the artwork in terms of disparity variations alone increases the required effort significantly compared to traditional monoscopic techniques. This appears as a valid reason to explain why many stereoscopic handmade works, especially paintings, depict geometric shapes and objects, rather than real life compositions. Consistency and time, however, were not the only factors that forced the demise of stereoscopy.

Photography, that was invented almost concurrently with stereoscopy, functioned as a catalyst for the birth of new art movements. As Silverman writes "As a mere mechanical process, photography could not exercise the tasteful judgment of the human artist" [101]. Since monoscopic and stereoscopic photography allowed precise imaging of reality and particularly accurate depiction of spatial dimensions, artists turned away from realistic depiction and experimented with more expressive techniques the camera could not compete with. Willats [128, p.220–247] argues that artists' interest shifted from the use of traditional representational systems, such as perspective, and found alternative means of creating pictures that suggested flatness, rather than aiming for three-dimensionality. This was a shift in aesthetics, which had an impact on which techniques were to be used. Art movements such as Impressionism, Expressionism, Cubism, Op-art and various others emerged shortly after stereoscopy and photography were invented. While the Modernists were exploring new expressive picture-making techniques, stereoscopy remained mainly a photographic technique until the second half of the 20th century, when artists utilized it in pictorial representations to reintroduce the communication of depth [59, 36].

On the opposite end, the inability of the audiences to readily view stereoscopic artwork by free-viewing made it relatively difficult to disseminate the works of stereoscopic artwork. Artists equipped their exhibitions with stereo viewing devices to allow the audiences to see beyond the flat canvases. Free-viewing, or special stereoscopes, are necessary when viewing large stereo works. Printing stereo artwork (e.g. in books) in a smaller scale than the one they have been originally created compresses depth, since disparities are scaled down, and may render the artwork's spatial characteristics weak or imperceptible. If free-viewing were an ability possessed by most art enthusiasts, then stereo artwork may have become more popular.

According to Crary [23, p.127–136], the sociocultural demise of the stereoscope, around the turn of the 19^{th} century, was not strictly because of its association with pornographic images, as others have claimed. He argues that the simulation of reality by using the stereoscope required the observer to shift away from the classical viewing techniques of monocular pictures. Stereoscopy has brought around a new viewing technique that reconfigured the observer in relation to the visual representation. This was radical enough a change that stereoscopy, even in its 20^{th} century resurfacing, did not achieve to become a standard viewing technique and, therefore, its popularity receded again.

In the past two decades, however, stereoscopy was subtly integrated into Virtual and Augmented Reality systems. The quality and ubiquity of such systems have improved rapidly and have become acceptable by the targeted audiences, especially for applications in domains where realistic simulation of percepts is important. Stereoscopy has also penetrated the environment of the home user. Three-dimensional games and applications can now be used in combination with affordable stereoscopic systems. However, the stereoscopic technique is not a main objective for most 3D software makers, since the market is still relatively small.

Chapter 3

Related Work

The broader goal of this work, which is to turn 2D stereoscopic images into artistic-looking picture pairs, presents us with a number of problems that implicate techniques from different areas of computer science.

We assume in this work that decoupled imaging devices (i.e. digital cameras) are used in a stereoscopic formation for input acquisition. This approach is more flexible than requiring specialized stereoscopic hardware and allows a variety of devices to be used with the rest of the rendering system implementing our algorithms. This increased flexibility of attaching arbitrary devices comes with the price of requiring to manipulate the acquired images in order for the image pairs to be suitable[1] for processing by stereo analysis algorithms.

In fact it is more of a rule rather than an exception that the two imaging devices will have variable imperfections on their sensors as well as other deviations in hardware construction. This means that even if the two devices are arranged carefully side-by-side, the 2D images captured may still not be suitable to directly be utilized for stereoscopic analysis or synthesis. To create a proper stereoscopic coupling between the two input devices, their image planes must be reprojected to ensure that their geometry allows further processing.

The requirement of using 2D images of real scenes as an input from the onset of the work suggests that traditional rendering techniques using 3D geometric objects cannot be directly applied. Instead, to generate stereo views we use principles from Image-Based Rendering (IBR) techniques to generate new renditions from images, rather than geometric objects. An important consideration in this work is that selective rendering of features in the new stylized stereo views cannot be readily performed, since high-level information of scene structure is absent. Thus we recover some of the underlying geometric information in the scene (i.e. depth) using stereo vision. We can then selectively apply artistic filters on the extracted objects or features based on this information. Because depth is critical in the comprehen-

[1] In the context of this work, the acquired image pairs become suitable for stereoscopic image analysis after bringing them into an epipolar geometry, in which the horizontal scanlines of the one image correspond to the equivalent scanlines of the other image, as described in Section 3.2.

sion of stereoscopic space, this gives us an advantage over single-view algorithms, which usually treat images as flat surfaces and apply effects selectively using either 2D features, frequency, or saliency information in the image. While this information provides in many cases adequate input for selecting and highlighting specific features in an image, these techniques are solely based on monocular depth cues already present in the image. Furthermore, in a stereoscopic context, without establishing an appropriate correspondence of features between the two views (which is a major focus in this work), applying an algorithm separately on the two input images will result in new images that may be inconsistent. However, while some inconsistencies may be tackled via appropriate processing (e.g. in the same sense temporally coherent algorithms are applied to an image sequence), selective rendering of features according to their distance from the viewpoint will not be possible. The latter prevents such techniques from automatically manipulating stereoscopic features, and manual intervention is therefore required to apply rendering styles selectively according to scene depth.

Turning photographic images into artistic-looking pictures requires both image analysis and synthesis procedures. Creating such human-oriented renditions usually requires the modeling of natural media or simulation of traditional picture-making techniques in a consistent manner that is meaningful, in order to provide output that is appropriate for stereoscopic viewing. We will look for solutions to the synthesis of artistic-looking images mainly in Non-Photorealistic Rendering, but in a hybrid context in which computational stereo vision is first used to recover scene structure. Then stereoscopic view synthesis is employed to handle the consistent generation of the stereo views and selective NPR is applied to artistically augment the stereo views.

3.1 Image-Based Rendering

Image-Based Rendering techniques concentrate around the concept of synthesizing images by using existing input images. In contrast to computer graphics geometry-based rendering methods, IBR provides an alternative set of methods to solve the image synthesis problem without the requirement of explicit 3D geometry. Another main advantage of IBR over traditional 3D computer graphics methods is that the input image samples required to generate new views of a scene can be easily acquired with imaging devices. In IBR, images are the rendering primitives, rather than polygonal meshes, which also indicates that performance of IBR techniques is independent of scene complexity. High fidelity images can be synthesized much faster than by utilizing computer graphics methods. In essence, however, IBR is not a replacement for computer graphics, but rather an alloy of techniques that use both computer vision and computer graphics, attempting to benefit from the best of both worlds.

Although IBR techniques and systems are younger than geometry-based 3D computer graphics, a large body of scientific literature has been formed around them and several surveys [57, 100, 131] provide a more detailed overview of this emerging research area. According to Shum and Kang [100], the spectrum of IBR techniques can be divided into three categories that characterize algorithms according to their dependency on geometric information, as shown in Figure 3.1.

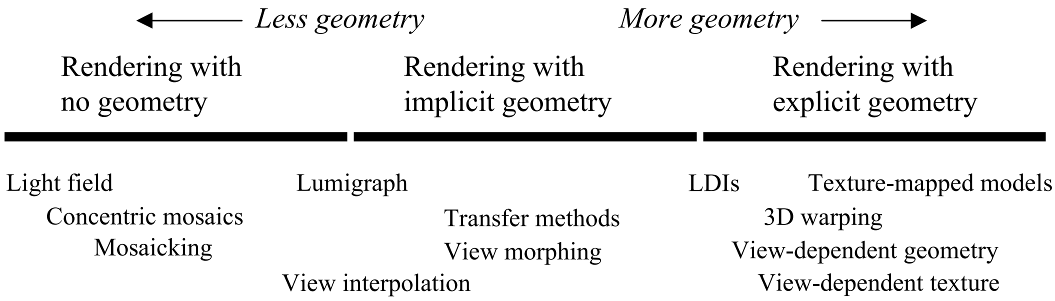


FIGURE 3.1 *Categorization of image-based rendering techniques (from [100]). (LDIs stands for Layered Depth Images.)*

3.1.1 Rendering without Geometry

On the one end of the spectrum, techniques that do not require any geometry, such as the light field [62, 61], produce increasingly better results as the number of available image samples increases. The lumigraph [41] is a technique similar to light fields, but differs slightly in that it also uses approximate geometry estimated from silhouettes in order to increase the quality of the synthesized views. In this category of non-geometry-based techniques also belong mosaicking methods (e.g. concentric mosaics [99]) and panorama methods [113], which are the basis of many spherical and cylindrical panoramic image systems.

Most of the non-geometry-based IBR techniques are based on the 7D plenoptic function [1]:

$$P_{7D} = P(\theta, \phi, \lambda, t, V_x, V_y, V_z), \qquad (3.1)$$

which theoretically models the intensity of light rays passing through an idealized eye placed at every point (V_x,V_y,V_z) in a scene observed from every possible angle (θ,ϕ), for every wavelength λ, at every time t.

The complete plenoptic function (Eq. 3.1) is 7D and it is technically impossible to fully reconstruct it. Therefore, most systems based on it set constraints (e.g. consider the scene to be static) to reduce the high dimensionality of the plenoptic function in order to arrive at a viable approximation that can be practically used. For example, 2D panoramas with a fixed viewpoint (e.g. [17]) can be obtained by reducing the plenoptic function to:

$$P_{2D} = P(\theta, \phi)$$

Due of the nature of the plenoptic function, practical systems require multiple samples to be acquired and used to resample the light rays of the plenoptic function in order to synthesize novel views, which results in a requirement to efficiently compress and store the samples.

3.1.2 Rendering with Implicit Geometry

Methods of this category are implicitly dependent on geometry. Usually computer vision techniques are employed to establish feature correspondence between the available views, and projective geometry is mainly utilized to generate the new views. The number of image samples used is much smaller than those required for IBR without geometry, but recovering the correspondence between pixels or features in the input views may be computationally intensive. Notable techniques are the view interpolation [17], view morphing [95] and view synthesis from stereo [92], as well as projective transformation methods using epipolar constraints in pairs of images or trifocal tensors when three images are available [44].

View interpolation uses “morph maps”, which are maps providing a forward per-pixel mapping from the one input view to the second. Then linear interpolation is used to approximate the perspective viewing matrix of the desired view in order to generate it. View morphing is a shape-preserving image transformation that produces a new image using two input images, their respective projection matrices, as well as a pixel correspondence map. The correspondence map in this case is derived by a combination of user-defined correspondences in the two images and automatic interpolation via the use of image morphing techniques. View synthesis via stereo vision techniques relies on using stereoscopic configurations to solve the novel view image synthesis problem. This is achieved by first recovering the distance of each point in the observed scene to the viewpoint using stereoscopic projective geometry, via stereo matching, and then, by using image warping, a new image is generated that corresponds to a hypothetical new camera pose. Since many aspects of stereo, not directly associated with novel view synthesis, play a central role in this work, we treat it later in more detail. All the above methods are particular cases of more general approaches that share the common characteristic of using fundamental matrices or trifocal tensors to establish the correspondence between input samples in order to derive novel views.

3.1.3 Rendering with Explicit Geometry

On the other end of the IBR spectrum, techniques use representations that incorporate incrementally more 3D information. These include popular algorithms and their variations such as 3D image warping [67], layered depth image [96] and view-dependent texture mapping [26]. 3D image warping is based on the concept of using existing depth values to project input pixel values from 2D to 3D space and then reproject these values to the image plane of the desired novel view. The layered depth image representation [96] can be used to store multiple depth values for a single pixel across each line of sight using a single camera, describing not only the visible surfaces across each ray, but also surfaces that are occluded. Then, according to the visibility of a surface, the appropriate depth values can be used to synthesize the desired novel view. In view-dependent texture mapping the goal is to use a set of input images to texture map existing geometry from novel views. The visibility of each polygon is resolved and then "view maps" are constructed to allow efficient selection and blending of input images for the generation of novel views by projective texture mapping.

3.2 Computational Stereo Vision

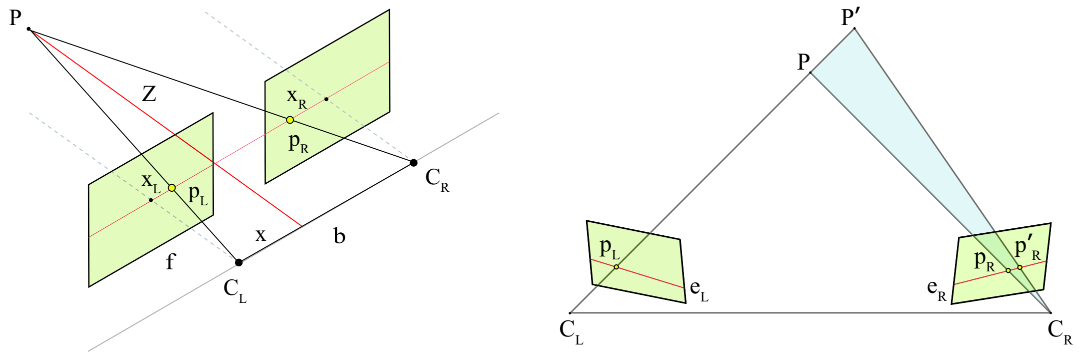
We have described in Section 2.2 the principles of stereoscopy from a standpoint not related to computer science. In this section we revise this information within the context of computer vision and specifically within the scope of computational *stereo vision* research, which is interested in the recovery of depth information of a 3D scene using two or more images acquired through specially selected viewpoints.

Stereo vision is used to establish a set of scene point correspondences between the reference views, without fully describing the imaged objects. Similarly to how the human visual system estimates depth from binocular vision, the input from a camera stereo rig can be used to identify the disparity between features in the two stereo projections. Disparity can in turn be used to infer the distance of a given scene point from the sensors. Of course depth estimation of scene points that are not visible from both viewpoints cannot be performed directly, however assumptions can be made about these occluded regions in order to assign a depth value, if the scene points are visible at least from one of the viewpoints. Various strategies have been proposed in the literature that aim to counter this fundamental problem of resolving visibility (e.g. [13, 109]). The process of finding scene point correspondences in the two stereoscopic views is widely known as *stereo matching* in computer vision, while the family of techniques inferring depth values from scene point correspondences by using stereo matching is usually referred to as *depth-from-stereo*.

To estimate depth, stereo algorithms attempt to locate the images of 3D points in space on the respective image planes. Determining the exact position of the same point in the images is usually referred to as solving the *correspondence problem*. The shift of a projected point between the image planes is referred to as *disparity* and can be used to infer the distance of the actual point in space to the viewpoint. By solving the correspondence problem for all points on the image plane a *dense disparity map* is estimated. In some applications where the disparity of the complete scene is not of interest, specially crafted stereo algorithms can be used to selectively recover disparities for specific features only (e.g. object silhouettes), in which case a *sparse disparity map* is estimated.

To acquire the stereoscopic digital images and use them to infer depth, two imaging sensors are usually used in a side-by-side arrangement so that they are parallel and horizontally displaced. Alternatively, the same sensor may be used to acquire two images of a stationary scene by sequentially capturing an image from different positions. In either case, it is important to determine the *extrinsic* and *intrinsic* parameters of the camera system. Extrinsic parameters describe the relative position and orientation of each camera to the world's coordinate system, while intrinsic parameters model the internal geometry of the cameras, usually the focal length, optical center and lens distortions. Both parameter sets can be estimated using various calibration techniques, presented in [46, 133]. For most stereo algorithms, the accuracy of the calibration has a direct effect on the quality of the correspondence results; poor calibration usually leads to poor disparity estimates, while accurate calibration leads to better results.

Consider two optical centers C_L and C_R of a left and right camera, e.g. as in Figure 3.2(a), imaging a scene point P to respective image projections p_L and p_R that have coordinates x_L and x_R on parallel image planes. If the baseline b is the distance between C_L and C_R and the focal length f is the distance of the optical center to the image plane, then the disparity d of point P is the displacement of its projection between the left and right views — with the left as the reference view —



(a) Simple stereoscopic geometry (b) Epipolar geometry

FIGURE 3.2 *Using epipolar geometry to constrain the search for point correspondences along epipolar lines.*

and can be calculated as follows:

$$d = x_L - x_R \tag{3.2}$$

From similar triangles it can trivially be derived that

$$\frac{x_L}{f} = \frac{X}{Z} \quad and \quad \frac{x_R}{f} = \frac{X - b}{Z} \tag{3.3}$$

Then by substituting equations 3.3 into equation 3.2 we have:

$$d = \frac{fb}{Z} \tag{3.4}$$

For a fully calibrated stereo system the focal length f and the baseline b can be considered known and constant, effectively enabling this stereoscopic geometry to be utilized to infer the depth Z, which is inversely proportional to the disparity d, as can be seen in equation 3.4.

In practice, however, camera systems, even when they are comprised by identical devices, have different intrinsic parameters and their image planes may not be perfectly parallel, despite careful configuration. Therefore, matching points in the respective image planes requires for each pixel the whole respective image plane to be scanned. This search space is prohibitively broad, as well as unnecessary. Consider that a 3D point visible from the left camera, such as p_L, defines a projection ray passing through the optical center C_L. Since we assume that the point is also visible from the right camera there exists an image of this ray on the image plane of the right camera, which is known as the *epipolar line* e_R, see Figure 3.2(b). This *epipolar constraint* can assist stereo matching algorithms to reduce the computational effort and probability of errors in solving the correspondence problem by enabling them to search for a match for any given projection of a point P in one image plane along the corresponding epipolar line in the other image.

Epipolar lines are the intersections of the epipolar plane, that is the plane passing through C_L, C_R and P, with the image planes, as shown in Figure 3.2(b). In the general case, this search along the epipolar lines is a 2D search. By further reprojecting the two image planes on a common image plane that is parallel to the baseline, as the one we have assumed in Figure 3.2(a), this search can be reduced to a 1D scanline search. The procedure of reprojecting the image planes parallel to the baseline so that scanlines correspond to each other is known as *rectification*. Popular rectification algorithms commonly used in stereo vision include, but are not limited to, those proposed in [64, 45, 66].

Deriving disparity maps is one of the most researched problems in computer vision and a multitude of techniques have been proposed. While this section has presented a short description of how a stereoscopic geometry can be set up to perform stereo vision computations, comprehensive surveys describing the fundamentals of computational stereo vision as well as various algorithms that solve the correspondence problem can be found in [7, 30, 92, 14].

3.3 Digital Stereoscopic Imaging

Pairs of images that obey a stereoscopic geometry can be either acquired or synthesized. Acquisition can be performed using a variety of digital devices. The most common digital stereoscopic imaging configurations are two: (a) pre-manufactured optical stereo cameras and (b) individual digital cameras coupled in stereoscopic configurations.

Pre-manufactured optical stereo cameras are special purpose devices engineered to readily capture images that are stereoscopic, such as PointGrey's BumbleBee camera shown in Figure 3.3(a). These devices feature two imaging sensors bundled into the same device and synchronize image acquisition between the two sensors. In addition, they expose the stereoscopic system's intrinsic and extrinsic parameters. They are easy to calibrate, and provide directly rectified and undistorted images, as well as depth information, even at interactive frame rates. The downside of using these devices is that they are currently more expensive when compared to other options. Also they must be attached to and operated by a workstation computer system, and thus are not suitable for outdoors stereo imaging. In addition, the extracted depth information may not be adequate for every application and therefore extra processing may still be required.

Digital cameras coupled in stereoscopic configurations are pairs of single-sensor cameras that are configured and adjusted independently from each other, by the end-user, to form a stereo rig. These stereoscopic systems are more flexible than the fixed depth cameras and can potentially lead to very affordable or very high-quality stereo configurations, depending on the price and quality of the individual devices used. The typical approach is to use two identical devices on a side-by-side arrangement and provide some mechanism to synchronize image acquisition. Low-end stereo rigs use commodity digital photographic cameras and are popular among stereo photography enthusiasts. Both cameras can be triggered by pressing a single (usually custom) button. These configurations are usually mobile, but do not provide any information about the intrinsic and extrinsic parameters of the stereoscopic system and thus are mostly suitable for conventional stereo photography. In contrast, stereoscopic rigs that are formed by using more advanced computer-operated digital imaging devices, such as the PointGrey's DragonFly cameras shown in Figure 3.3(b), enable users to acquire synchronized images and videos from the two cameras and can apply a number of computer vision algorithms to calibrate, rectify, undistort and extract depth information from them.

(a) (b)

Figure 3.3 *(a) PointGrey's Bumblebee, a commercially available stereoscopic camera,(b) stereo rig using two PointGrey DragonFly cameras.*

Alternatively, synthesis of stereo views can be achieved easily by using existing computer software based on 3D computer graphics. The idea is to render the 3D scene from two spatially displaced virtual cameras, simulating a binocular visual system, similar to the setup shown in Figure 3.4. Nevertheless, while the setup of stereoscopic virtual cameras may be very simple, the availability of high quality models and textures limits the applicability of such systems in a broader context.

Rendered views are relatively restricted in content and realism and may take a significant amount of time to calculate, when compared to those that can be acquired with imaging devices. The task of manually creating 3D models and textures is both time-consuming and resource-demanding, therefore alternatives are sought, not so in the direction of improving existing 3D algorithms, but more in the direction of merging and integrating them with computer vision techniques. An obvious step toward this direction is to either use input images of IBR systems to generate novel views that are stereoscopic, or use techniques of IBR within 3D computer graphics software systems to speed up computations. In this context it has been shown that IBR methods can be utilized to generate partially the second view from the first, using the geometric correspondences that can be easily derived within a 3D system. For example, Adelson et al. [2] discuss how the stereoscopic perspective projection can be used in a 3D rendering system in order to optimize various traditional 3D algorithms, such as polygon rendering, polygon and line clipping and hidden surface elimination. Wan et al. [121] present a system for interactive stereoscopic rendering of volumetric environments. They first generate a depth map and the left reference image by using volumetric ray casting. They constrain the virtual viewpoints so as to obey a stereoscopic projection that allows them to warp most of the left view to the right using the depth map for the reprojection of splats[2]. They then directly ray cast the volume from the right viewpoint in order to fill in holes in the right image.

The above discussion leads us to the conclusion that stereoscopic image synthesis is possible using independently computer vision or computer graphics methods as the starting point. Nevertheless, a combination of properties from both areas allows more flexibility and can counter to some extent the various drawbacks presented by each.

3.4 Non-Photorealistic Rendering

Non-Photorealistic Rendering, in contrast to photorealistic approaches, aims to produce images that stimulate not only the optical nerves, but also trigger the mental abilities of our higher-level cognitive mechanisms. Advances in NPR have enabled computers to simulate natural media [19, 9, 70, 82, 58] and artistic processes [87, 47, 105, 39]. The majority of these algorithms and systems are targeted toward producing a monoscopic rendition by processing geometry or images from a single viewpoint. Only recently, techniques that use multiple viewpoints have

[2]Splats are chunks of texture that are splatted, or forward-mapped, from a source onto a target texture.

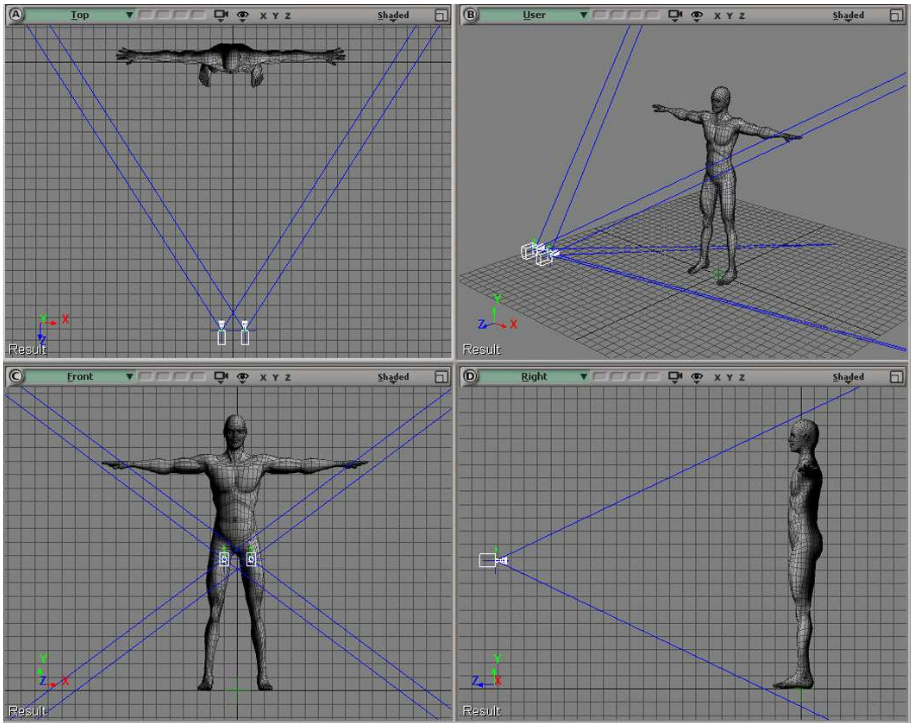


FIGURE 3.4 *Example setup of virtual cameras using a commercial 3D software package (Autodesk SoftImage|XSI) for stereoscopic rendering.*

emerged [27, 8, 104]. For extensive discussions and analysis of well-established NPR techniques, interested readers are encouraged to consult the two textbooks [40, 108].

Many researchers in the area discuss their goals and results as a simulation process of artistic techniques or media. This unintentionally downplays the visual importance of the generated non-conventional pictures. The real innovation achieved by NPR algorithms is the production of renditions that shift the boundary between computer-generated images and human perception toward the latter. Instead of overflowing the visual system with excessive and usually redundant information, the non-photorealistic picture streams already abstracted or stylized data that the observer does not need to process extensively. Furthermore, the picture maker, be it a human or a computer algorithm, will oftentimes intentionally enhance, within a given context, image features that suggest importance to the visual system. Therefore the synthetic non-photorealistic picture should no longer be considered as a mere simulant of a process, but rather as a human perception stimulant, and therefore its effectiveness is critical.

In the context of perceptually-driven image synthesis, Green [42] discusses NPR in contrast to photorealism and adapts the classification proposed by Teece [116]. In his Ph.D. thesis, Teece classifies various NPR techniques according to whether they are primarily 2D, $2\frac{1}{2}$D or 3D. He further categorizes them according to whether they require user intervention or they are fully automatic. Finally, he looks at the objectives of research, i.e. natural media simulation, image enhancement, artistic expression and animation. This classification, while adequate for categorizing most of the published research to that date, does not account for emerging technologies, such as stereoscopic NPR presented in this work. Even though it considers temporality of the objectives as a category itself (i.e. animation), it leaves out spatiality. We therefore propose that research is also differentiated by the spatial dimension of its intended outputs, which could be divided into 2D images, 3D models (i.e. stylized 3D models [80, 69]), novel NPR views generated by image- or example-based rendering and stereoscopic or other multi-dimensional approaches (i.e. holographic outputs) that may emerge.

In our work, we focus on stroke-based rendering [48], and of special interest are techniques that use depth information to enhance the appearance of the artistic composition by introducing valuable monocular depth cues. Strokes are marks strategically deposited on a substrate to convey shape and color in a picture. While strokes are modeled individually, usually following local information of a picture or a model, a collection of them is usually grouped perceptually to represent higher-level features in the final picture. Line drawing for instance is commonly performed by sampling data points describing a continuous line (e.g. an object silhouette) and then, using those samples, shorter and looser lines or parametric splines are fitted, similar to the way humans create drawings. An interactive system that uses spline fitting on user-supplied data points is described in detail in [79].

Strokes have been used in early graphical systems as means of human-computer interaction [110], but they have since evolved from simple line representation techniques into more elaborate descriptions of marks that not only simulate simple tips of media applicators, but also complex brushes. In general, some algorithms utilize strokes to simulate the way artists deposit marks on their working surfaces. Other algorithms use strokes to model the physical interactions of a medium, an applicator and a substrate. These techniques vary in the level of interactivity required. Early systems for drawing and painting, such as [102, 127, 107, 78], required a user to input the sample points along which strokes were drafted.

Haeberli [43] introduced his painting system that first generates automatically locations for brush strokes from an intensity color image and then lets the user drive the painting process by selecting at which of these locations strokes should actually be painted. He also describes extensions to this approach such as an automated painting procedure by relaxation. Around the same time Cockshott [19] proposed "Wet and Sticky", a physically-based painting system that models the interaction of color pigments with a substrate. Saito et al. [86] have introduced the use of Geometric Buffers, known as G-Buffers, to enhance the legibility and comprehensibility of their images. G-Buffers usually encode geometric information of 3D scenes into image buffers, such as surface normals, depth values, object IDs, and others. By using image processing techniques in a postprocessing step, G-Buffers are utilized to enhance selectively image features of the final renditions. Schofield [94] used G-Buffers in the Piranesi system, a hybrid interactive and 3D rendering painting system, to select object regions that users could then paint interactively. Similarly, other researchers [29, 75, 76] have used additional data extracted from 3D datasets in order to drive the NPR image synthesis step in their techniques. Curtis [24] uses a depth map to render stylized silhouettes around objects by generating a force field that guides a physically based particle system that erases ink from thick outlines initially drawn. Eissele et al. [32] have further proposed the G^2-Buffer framework, a graphics hardware implementation of G-Buffers that is useful for real-time GPU-based rendering. Even though most techniques differ in the extraction, representation and utilization of G-Buffers, they all present enhanced results over previous methods. In general, the concept of G-Buffers has become a norm in NPR techniques.

Litwinowicz [63] presented in detail a fully automated painting system, similar to that of Haeberli [43], that uses image gradients to orient strokes, significantly improving the existing techniques and suggesting algorithms to incorporate optical flow, a motion estimation technique, in order to animate the painted images. Hertzmann [47] introduced curved brush strokes of multiple sizes that, by using an input image, are planned and rendered automatically to generate paintings in a variety of different styles. His technique uses a coarse-to-fine concept, where the foundation of a painting is roughly set by using large brush strokes and is then progressively refined with smaller spline brush strokes, similarly to how painters work; that is by first painting in the more uniformly colored areas and then progressively adding detail. One of the main reasons Hertzmann's work is significant is because it marries for the first time the older ideas of using simple straight lines for modeling the strokes in automated systems with the spline-based interactive painting techniques into a coherent automated algorithm that makes use of the best features of both approaches. Other notable advances in NPR around the same period were the pen-and-ink illustration system of Salisbury et al. [88] and the watercolor simulation system of Curtis et al. [25].

Later, Raskar et al. [81] have developed a novel hardware-assisted method to automatically create comprehensible illustrations of real images by using depth discontinuities to enhance legibility. They use multiple images taken by a multi-flash camera where cast shadows are used to detect depth discontinuities in the scene. These depth edges together with the original texture of the scene objects are stylized to convey and better communicate the important information of even complex scenes. To achieve good results, the technique requires that cast shadows can be detected and processed.

Bartesaghi et al. [8] presented a non-photorealistic rendering technique that uses multiple images to compute a single view. They infer geometric features, i.e. surface normals and principal directions, from stereo images and use them to generate pen-and-ink illustrations. They point out that the surface normals' recovery can be rather unreliable, especially when using disparity maps computed from stereo matching techniques. This of course is one of the main problems associated with image-based stereoscopic rendering techniques, since any inaccuracies in the stereo matching process are delegated to the successive processes of image synthesis.

A limited number of other techniques have proposed the use of depth information to prevent inadequate stylization of salient features. Shiraishi and Yamaguchi [97] use a depth map, computed by ray-tracing, to adaptively control the parameters of their image moment-based painterly rendering algorithm [98]. The technique adjusts the size of the stroke textures used, so that distant objects are approximated by larger strokes, whilst objects closer to the viewer are rendered with smaller strokes. They also use depth to introduce a mask that restricts each stroke to approximate only one object within the window that encompasses the stroke. Objects of the same color that lie at different depths are preserved as separate objects on the final painted image. This could be considered as a $2\frac{1}{2}$D stroke clipping, following ideas similar to 2D stroke-clipping algorithms, such as in the work of Litwinowicz [63]. Gooch et al. [39] use segmentation and morphological operations to automatically create paintings by planning and rendering a resolution-independent set of strokes. In the same work, an extension of the algorithm uses depth maps, computed from 3D scenes, to assist the segmentation process via which better results are reported on the final painted images. A discussion about depth-from-stereo, in the same work, also highlights the problems arising from such depth maps. A common characteristic of the algorithms using depth to enhance stylization is that they demonstrate results obtained using highly accurate depth information computed by ray-tracing of 3D scenes and, therefore, are not exposed to the problems present in the depth maps estimated by using depth-from-stereo.

Snavely et al. [104] process multiple video sequences of the same scene and apply a spacetime stereo technique to extract depth information. The $2\frac{1}{2}$D video sequences are then further processed to produce temporally coherent stylized animations. While their preprocessing steps are very similar to those of our setup, they do not direct their efforts toward the output of stereoscopic content, but rather they use temporal disparity maps to provide frame-to-frame coherent object segmentation and assist in the stylization process.

Available view independent rendering techniques based on 3D scenes, such as [56, 130], can potentially produce stereoscopic output since the artistic primitives used are attached and remain on the 3D model's surface, independent of the location of the viewing point. This, however, becomes particularly challenging in our research, since our techniques use images as their input which lack a geometric description of the underlying scene structure. Therefore, additional processing is required (e.g. recovery of depth information), which in practice may yield unreliable data. In general, algorithms that process 3D models can potentially render a scene from two horizontally displaced viewpoints to generate stereoscopic image pairs, however the requirement of 3D modeling poses a significant limitation.

Other methods to create stylized stereoscopic renditions of photographic images involve the use of image convolution algorithms found in many commercial image editing applications. Usually, these algorithms operate locally on a small pixel neighborhood and apply simple stroke models, edge detection and color filtering. They can potentially generate stylized stereo pairs by processing individually the two images, nevertheless they lack high level description of scene structure and therefore they cannot separate objects and treat them individually; neither can they simulate artistic media which require surface descriptions and elaborate stroke models.

All the techniques described aim to generate monoscopic content and do not provide stereo output, which requires consistent stylization on both stereo views. We also observe that NPR techniques using depth-from-stereo do not attempt to extract a geometric description of the scene objects in order to process them for an artistic effect in 3D. Most of these techniques use either reliable features (e.g. depth discontinuities) related to the extracted depth information or provide alternative mechanisms in the stylization process that compensate for those inaccuracies (e.g. adaptive resizing of strokes).

In the following chapters, we present a set of different NPR techniques which are based on processing stereoscopic input images, but instead of a single rendition they provide consistent stereoscopic image pairs.

Chapter 4

Preliminaries for Stereoscopic NPR

The first part of this chapter outlines the framework in which the connection between individual algorithms and their technical aspects pertain to our previous analysis of the stereoscopic medium in the domain of arts. The second part describes the common basis for all the stereoscopic Non-Photorealistic Rendering algorithms that are detailed in the subsequent chapters.

4.1 Stereoscopic NPR Framework

Based on the fundamentals of the stereoscopic medium in arts and sciences, we propose a practical framework of design and implementation considerations that stereoscopic algorithms for artistic content creation should account for. The components of the framework directly link computational techniques, methods and technical details to the goal-oriented design of stereo NPR algorithms.

This framework, acting mostly as a set of guidelines rather than as a formal ruleset, can further be modified and adapted by other single-view NPR algorithms to generate artistic stereoscopic content. It allows to devise a modular processing pipeline, described later, in which processing modules can be added or removed depending on the targeted algorithm. The modularization of the various processes allows for flexible modification of the generic pipeline to enable both speed optimizations and incorporation of other sub-processing algorithms, without significant modifications to the rest of the pipeline.

- *Feature Correspondence* - Features must be consistent across the two views. Artifacts, e.g. brush strokes that cannot be matched in both views, will inhibit stereo fusion and the viewers may experience discomfort. Large non-corresponding areas and deviations in color, or style, will produce similar undesired effects. The human visual system is able to tolerate a small percentage of inconsistency, which varies from person to person, but algorithms should strive on providing the best possible correspondence between the two stereo components.

- *Randomness* - Stochastic procedures used in generating artistic effects must be carefully designed so that the feature correspondence constraint is met. Non-Photorealistic Rendering techniques, such as [87, 63, 47], use random numbers to inject irregularity into the artistic process. In image-based stereoscopic NPR, randomness must be as consistent as possible across a stereo image pair, so that irregularity can be equally modeled within the two views. Perturbation functions applied on stylization parameters must also account for the desired consistency.

- *Performance* - Stereo pairs exhibit correlative information between their images that can be used to optimize the performance of a variety of algorithms (e.g. compression algorithms [91] or rasterization [2] of stereo pairs). Automated NPR algorithms can take advantage of the stereo pair relationships (i.e. stereo disparity) to reduce the computational effort of planning or rendering of the artistic images.

- *Depth from Stereo* - Disparity maps acquired by using automated computer vision algorithms, such as stereo matching algorithms [93], cannot be used to perfectly reconstruct a scene and they often encode artifacts that falsify depth information of scene points. Establishing a feature correspondence by using imperfect depth-from-stereo information may inhibit the artistic process. Artistic algorithms that use such depth maps have to be able to counterbalance the inaccurate geometric descriptions of the scene objects, without degrading the quality of the final artwork. It must be noted that it should be preferable to trade off artistic fidelity for consistency, since in stereo viewing inconsistencies have an unpleasant effect on the viewers.

- *Texture Continuity and Occlusions* - Occluded regions in stereo imaging, which are sets of points in the scene not visible from both viewpoints, must be specially treated. When viewed stereoscopically, occlusions have no correspondence and cannot be fused, however they must be filled in with appropriate content. In an artistic process, the style and color over an occluded region must seamlessly blend with the surrounding regions for perceptual consistency. Since occlusions have no representation in a feature correspondence map, such as a disparity map, their distance from the viewpoint cannot be computed and assumptions have to be made. The assigned depth values for occluded regions are usually extrapolated depth values of surrounding areas (e.g. using background depth values).

- *Paint Spilling* - Paint spilling practically occurs when color that is naturally expected by the viewer to belong to one object appears to extend to another object which lies at a different distance. This usually happens because of inaccuracies encoded in the depth map used, e.g. due to the common effect of block-based stereo matchers that "fatten" the foreground objects in the disparity map. It can also be a side effect of consistently applying a random function to the parameters of the composition elements. Generally, we call *paint spilling* the result of composition elements being inadequately extended across surfaces that are at different depths. Intersurface paint spilling does not necessarily degrade the quality of the individual stereo components, however, when the two components are viewed stereoscopically it becomes rather noticeable.

4.2 Stereoscopic Rendering Pipeline

We set up a stereoscopic rendering pipeline that takes advantage of the stereoscopic projection geometry that we constrain our image inputs to be within. Contrary to the method of Wan et al. [121], we use real images captured from cameras and, hence, a preprocessing step is required to establish the stereo correspondences between the two views. This task is usually computationally intensive and does not allow us to perform it at interactive frame rates. To overcome this limitation we detach the stereo matching process from the core artistic stereo synthesis algorithms and perform it as a preprocessing step.

The general form of our stereoscopic processing pipeline, shown in Figure 4.1, can be described as follows:

Preprocessing:

- Capture a left and right image from a calibrated camera stereo rig.
- Rectify and undistort the two image planes, so that a raster scanline in the resulting rectified left image (I_L) corresponds to the equivalent scanline of the right image (I_R).
- Apply a stereo matching algorithm (or any other auxiliary algorithms) to extract $2\frac{1}{2}$D scene descriptions.

Stereo NPR Processing:

- Apply a Non-Photorealistic Rendering algorithm to I_L to generate the left stylized view (C_L).
- Using the auxiliary scene representations (e.g. disparity map, occlusion mask), propagate style from C_L to the right view to generate a partially stylized right view (C_R).
- Optionally, process the partially stylized C_R to fill in any occluded regions.

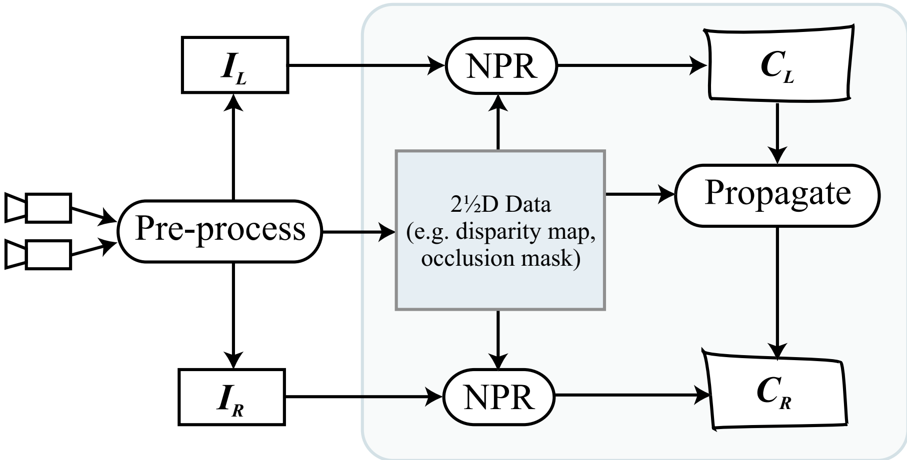


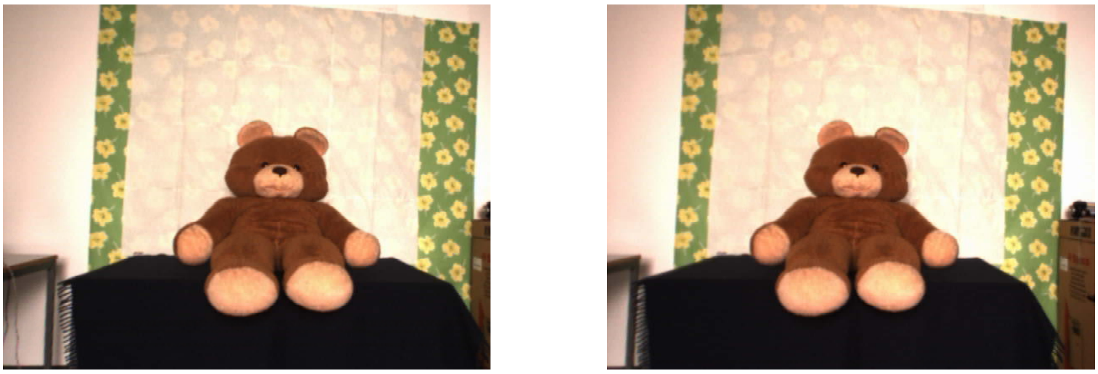
FIGURE 4.1 *General form of the image-based stereoscopic Non-Photorealistic Rendering pipeline.*

The distinct advantage of separating the calibration, image rectification and other potentially computationally intensive algorithms, such as stereo matching, into a preprocessing step is that various NPR stereo algorithms may use the extracted auxiliary buffers in different ways, producing in real-time or interactively a wide gamut of NPR stereo pairs. In fact, it is the propagation of style between the two views that can significantly boost the performance of our algorithms when compared to NPR algorithms operating on a single view.

The generic form of our pipeline can be modified according to the desired output. As we will discuss later, some algorithms can infer the whole second stylized view directly from the reference view, while other algorithms may require additional processing steps to fill in occluded regions or correct other inaccuracies. Nevertheless, the basic architecture of the pipeline remains intact and additional algorithms can be attached according to the application at hand.

4.3 Setup for Stereoscopic NPR Algorithms

The algorithms described in the next chapters all use an image pair that is acquired from two spatially displaced cameras. Since we are using decoupled digital cameras that do not have the properties of the ideal pinhole camera model, we employ standard calibration [133] and rectification [35] algorithms to turn the devices into a stereo rig with known epipolar geometry. Calibration is used to identify the intrinsic and extrinsic parameters of the camera system and rectification transforms the image planes so that their scanlines are horizontally correspondent between the left and right views. The images are also undistorted prior to being rectified to counter the effects of lens distortions. The corrected images are denoted as I_L and I_R, respectively. A sample rectified stereo image pair captured with our system can be seen in Figure 4.2.



(a) (b)

FIGURE 4.2 *The "Brown Teddy" dataset shown here is an example stereoscopic image pair captured by our calibrated camera system. Figures (a) and (b) show the left and the right stereoscopic components after rectification, respectively.*

A scene point visible from both cameras is projected to a pixel $p(x_L, y_L)$ in the left image and pixel $p'(x_R, y_R)$ in the right image, as shown in Figure 4.3 (top). The vector describing the pixel distance between these pixels is the disparity vector $\vec{d} = \vec{p_L} - \vec{p_R}$. Since we have a horizontal correspondence of features between the two images in epipolar geometry ($y_L = y_R$), the disparity vector will be $\vec{d} = ((x_L - x_R), 0)$, as shown in Figure 4.3 (bottom-right). The magnitude of $\vec{d}$ is encoded as a gray value in the disparity map, in the geometry of the reference view, shown in Figure 4.3 (bottom-left).

Using automated stereo matching techniques [93] we can compute a disparity map. In our experiments we have utilized the pixel-to-pixel stereo matching algorithm proposed by Birchfield et al. [10], as well as the more recent graph-cut based algorithm proposed in [12]. Example disparity maps extracted using the two

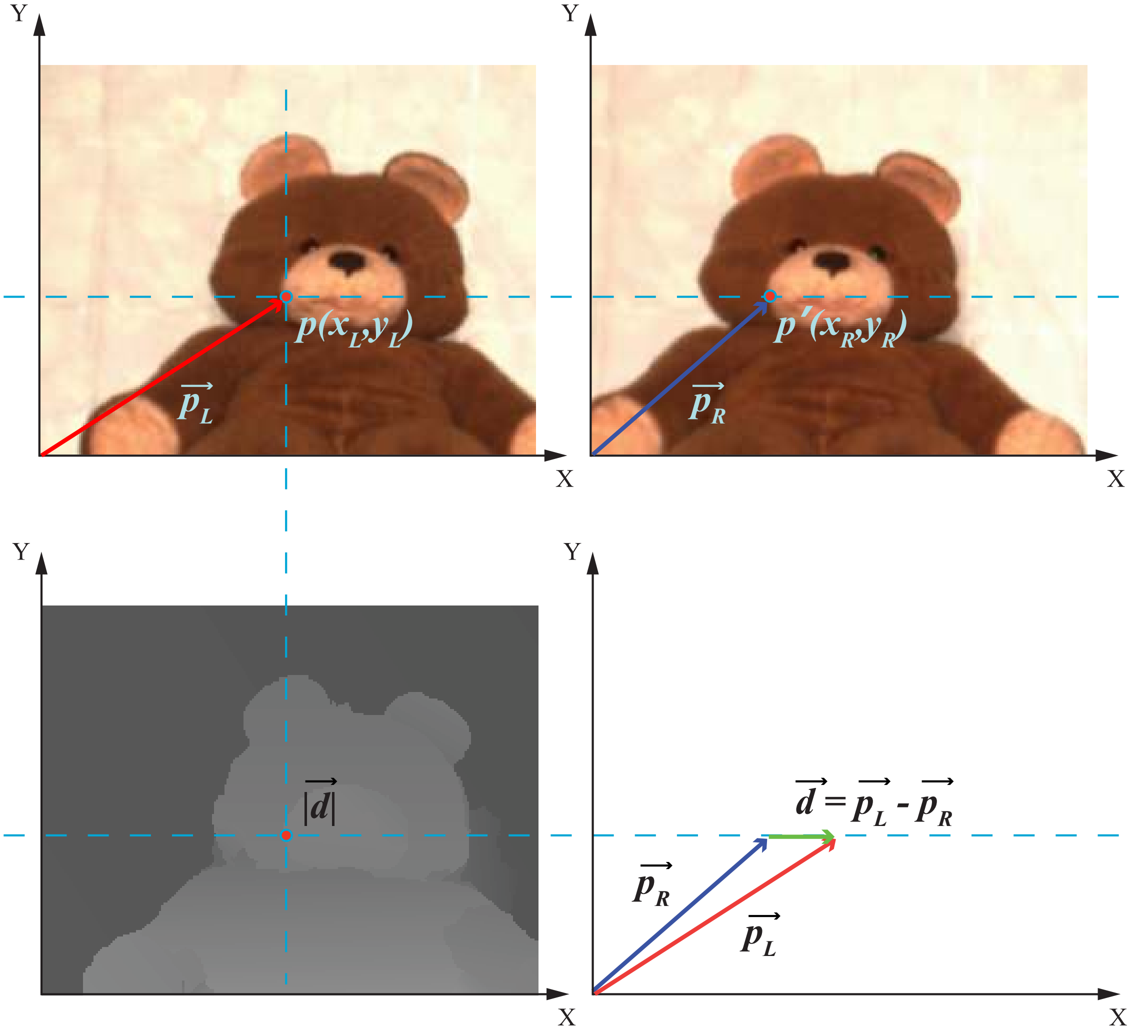


FIGURE 4.3 *In a stereo image pair with left and right images (top-left and top-right), a scene point is projected to p and p′, respectively. A disparity map (bottom-left) calculated via stereo matching encodes the magnitude of the translation vector $\vec{d}$ as a gray value that, when applied to p, provides the location of p′. The sign of the vector depends on which of the stereo images is considered as the reference view when solving the correspondence problem.*

methods can be seen in Figure 4.4. The algorithms used to establish the stereo correspondence between the two images can be exchanged in our modular pipeline, allowing new algorithms that calculate stereo disparities to be used with the stereoscopic NPR algorithms.

(a) (b)

FIGURE 4.4 *Disparity maps extracted using (a) Birchfield's and Tomasi's [10] and (b) Bleyer's and Gelautz's [12] methods.*

We note that estimated disparity values are inversely proportional to the distance of each scene point from the viewpoint and therefore a depth map (I_{depth}) can be inferred from a disparity map ($I_{disparity}$) by using

$$I_{depth} = s \cdot \frac{1}{I_{disparity}} \tag{4.1}$$

where s is a scaling factor that depends on the stereo configuration. In addition, the disparity map can be used to transform the reference stereo view, either the left or the right one, into the geometry of the other view. This can be achieved easily by doing a forward mapping of p by using the translation vector $\vec{d}$, or in reverse, with a backward mapping by applying $\vec{d}$ to p'. Equivalently, if the disparity map is calculated in the geometry of the second view, the roles are inversed and the second view is considered as the reference view.

The pixel-to-pixel stereo matching algorithm of Birchfield and Tomasi [10] uses dynamic programming to minimize the dissimilarity between pixel intensities along individual corresponding image scanlines and subsequently reduces unmatched pixels by propagating reliable disparities between scanlines. The algorithm behaves well for images with large untextured regions, using the assumption that intensity variation accompanies depth discontinuities. In contrast to other algorithms, it is specifically designed to identify depth discontinuities, at the expense of accurate scene depth reconstruction. Since depth discontinuities are explicitly used in some of our NPR algorithms, i.e. to identify and render object outlines, this stereo matching algorithm offers an alternative to more computationally intensive methods that provide more robust depth estimates across the whole scene.

The stereo matching algorithm of Bleyer and Gelautz [12] solves the correspondence problem by using a graph-cut based optimization technique. The rectified input images are color segmented and within each segment disparity is considered to vary smoothly. These disparity segments are clustered into layers which are likely to describe scene objects by minimizing a global cost function through graph-cut optimization. While this algorithm performs slower than [10], the stereo correspondences are more accurately recovered. The algorithm can handle scenes with large untextured regions and occlusions. Occlusions, treated symmetrically in both views, are handled by assigning them to neighboring non-occluded segments and then extrapolating reliable disparity values of the visible segments to the occluded ones. The advantage of this algorithm is that disparities are smoothly interpolated over single surfaces and the depth discontinuities are properly localized at real object boundaries. In addition, the layers extracted in the stereo matching process can be used as an auxiliary buffer in successive image synthesis steps, as we will show later in Chapter 6, when we present a distance-dependent NPR technique.

Stereo-derived depth values can normally only be computed for those pixels that are visible in both the left and right image. This means that for some scene points the depth values may not be possible to be inferred. Whenever required, we estimate and reconstruct the missing depth values by using reliable neighboring depth values. We store the locations of those pixels, usually a small portion of the whole image, in a binary map, which we refer to as the occlusion map. The occlusion map can be computed for both the left and the right view, if disparity maps are given in the geometry of both views. The pixels encoded in the occlusion mask require special consideration during the image synthesis steps further down the processing pipeline, as correspondences are not present in the disparity maps.

Chapter 5

Stereoscopic Drawing

Initially, stereoscopic line drawing has been used to communicate the essentials of stereoscopic vision by Wheatstone [125, 126]. Thereafter, stereo drawings can be found in comic books [15], as self-contained artwork [37] or even as an effective medium to convey the third dimension of scientific data (e.g. molecular formations [53] or medical illustrations [4]). The construction of stereoscopic drawings by hand is a rather tedious task and it has been very scarcely treated in art literature.

As the line has tremendous utility in monoscopic artwork, since it provides valuable depth cues, similarly its use within a stereoscopic context contributes positively to the construction of effective content. Sketches or simple concept drawings made out of lines, usually of a single color, lack many of the monocular cues found in other art forms. Shades and light, texture and atmospheric effects are mainly absent and therefore depth becomes less apparent. With stereoscopy the absence of these cues does not impair the perception of depth. Flat artwork, even made out of simple lines describing unfamiliar objects, can emerge in three-dimensional space with the use of correctly constructed stereo components. Adding outlines to objects at different distances in stereo pairs hints the observers' perception on the interposition of objects. Silhouettes and outlines, even when these are partial, assist the observer in the perceptual decoupling of the depth layers in the scene. The utility of stereoscopic concept drawings and sketches is also important for the foundation of other works, such as color illustrations and paintings.

We describe here an image-based method for automatic computation of stereoscopic concept drawings. Within our stereoscopic processing pipeline, we integrate basic digital image processing algorithms and line rendering techniques to create stereoscopic sketches that are both accurate and appealing. Our goal is to create simple stereoscopic line drawings that provide depth cues for the comprehension of the 3D structure of a stereoscopically imaged scene, without the use of known geometry (i.e. 3D models).

The main challenges we are presented with here are two. First, the extraction of silhouettes and other feature lines with standard image processing techniques, such as edge detection, may introduce visual clutter in the stereoscopic result. Intensity discontinuities captured by such algorithms will bias, and potentially confuse, the observer's perception of the scene's depth, since some of the detected features will merely capture texture discontinuities, rather than depth discontinuities. Since intensity image discontinuities captured by them are a superset of depth discontinuities, we would ideally want to extract only those lines that can assist the viewer to separate the depth layers of the scene. The second challenge, which is fundamental to stereoscopy, is to preserve consistency across the two generated stereo views. If edge detection is applied separately on the two images, which means that together with a subset of the intensity edges the depth discontinuities will be extracted, it is not guaranteed that the lines extracted for the left and right stereo components will be stereoscopically consistent.

To overcome these two shortcomings, we adjust our stereoscopic rendering pipeline to accommodate techniques that will extract only depth discontinuities and preserve consistency. As a byproduct of using the pipeline, the performance of the rendering algorithm is vastly enhanced by utilizing the established correspondence between the two input stereo images. In this specific algorithmic scenario, the second view can be fully derived from the reference view, without the need of additional expensive computation. Finally, the modular architecture of the pipeline allows the use of a variety of line rendering styles to be used with the stereo sketches. The stereo pipeline of Figure 4.1 is therefore simplified for this algorithm, as shown in Figure 5.1.

5.1 Stereoscopic Drawing Algorithm

To fulfill the requirement of extracting object boundaries that represent changes in scene depth, we use edge detection to detect depth discontinuities in the disparity map. However, since we want to simultaneously optimize the performance of the algorithm and preserve consistency, not all standard edge detectors can be used out of the box. Our approach in optimizing performance is based on the concept of style propagation between the two views. Instead of extracting features in both the left and the right views and then processing them for consistency, we extract features only in the geometry of the reference view (i.e. the left) and we then use warping to fully generate the right view, without further processing. To achieve this we constrain the extraction of image features to edges that are visible in both views, which implies that a value corresponding to the second view will be available for all

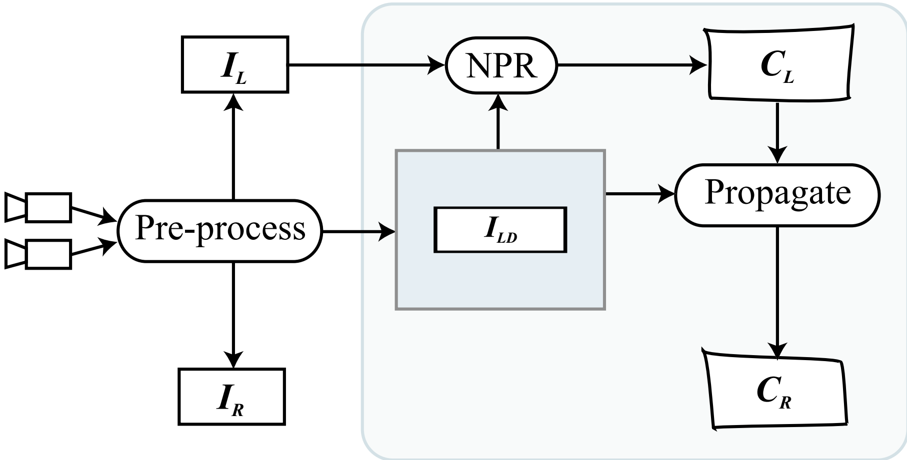


FIGURE 5.1 *The stereo pipeline for stereoscopic drawing. Since the complete right view is generated by using only the left drawing and the disparity map, the generic pipeline can be simplified. The NPR procedure in this case is a drawing procedure applied to I_L. The resulting drawing in C_L is then propagated to C_R by an image warping operation that uses the disparity map I_{LD}.*

those extracted features in the disparity map; therefore, propagation is guaranteed for the whole set of extracted pixels.

In short, our stereoscopic drawing algorithm consists of a feature extraction step, followed by a contour extraction, simplification and vectorization of the features.

5.2 Feature and Contour Extraction

A depth discontinuity is present in the image when a large change in disparity values is observed in the disparity map. The depth discontinuity can be used to select either the foreground or the background side of the discontinuity, depending on the application at hand. In our case, we want to detect the foreground object boundaries, since these are guaranteed to be visible in both views and therefore can be successively used in the style propagation step between the two stereo views. Foreground object boundaries have higher disparities, which are encoded with brighter gray values in the disparity map, and background objects are represented by darker gray values.

In this first step, we detect depth discontinuities by using edge detection. However, not all off-the-shelf edge detectors can explicitly detect the side of a discontinuity with the higher disparity. Some edge detectors, e.g. the Sobel and Prewitt edge detectors [38, p. 578], may mark pixels on both sides of the discontinuity, simultaneously, producing thick edges that are not exclusively on the foreground. These operators may also generate edges that trace a discontinuity contour with single-pixel accuracy, but along the same discontinuity some pixels are detected on the foreground object and others on the background. Other edge detectors, such as the Canny edge detector [16], tend to variably select, in the same image, discontinuities sometimes on the foreground objects and other on the background. Therefore these edge detectors are not suitable for our algorithm, since the extracted contours cannot be guaranteed to be on scene points visible from both viewpoints. As a result, propagating them from the first view to the second is not possible. A simple and very efficient alternative to these edge detectors is the Zero Crossings operator, which is based on the detection of the zero crossings in the response of a 2D Laplacian of a Gaussian (LoG) [68] filter applied to an input image. A comparison of the response of various standard edge detectors can be seen in Figure 5.2.

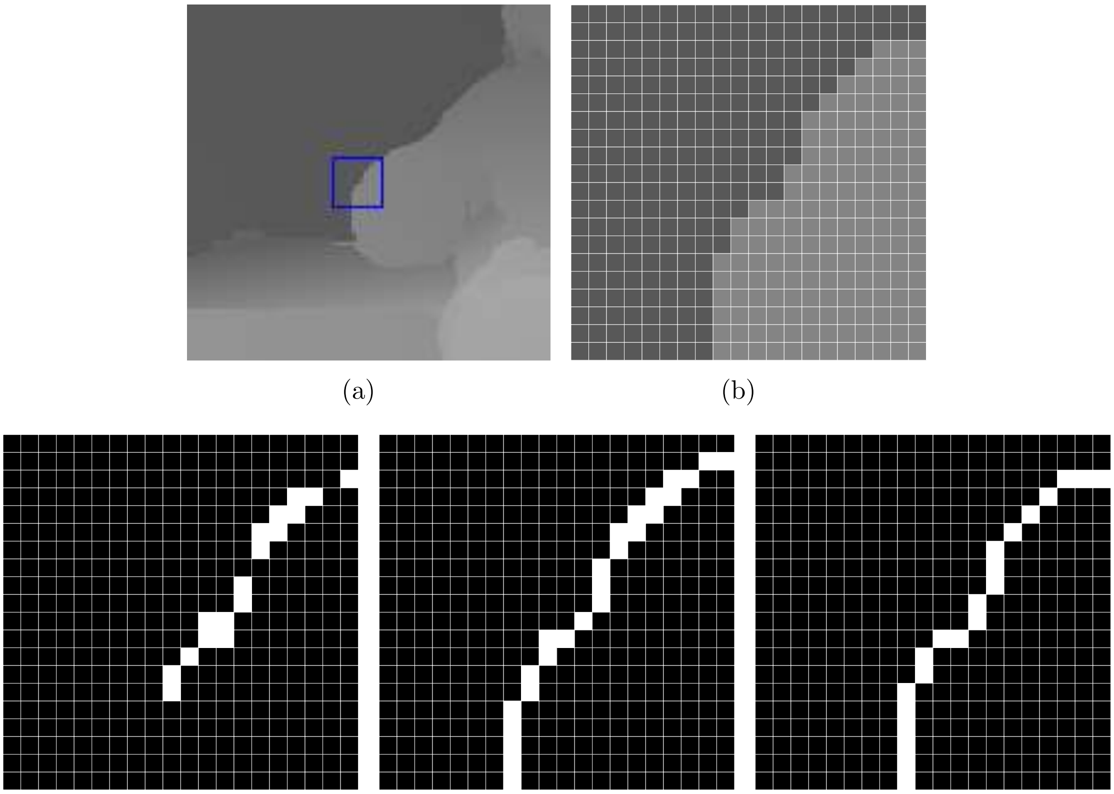
The LoG is a second order derivative:

$$\nabla^2 G(r) = -\frac{1}{\pi\sigma^4}\left[\,1 - \frac{r^2}{2\sigma^2}\,\right] e^{-\frac{r^2}{2\sigma^2}} \tag{5.1}$$

where $r^2 = x^2 + y^2$ in two dimensions and σ is the standard deviation of the Gaussian. This can be decomposed into a Gaussian smoothing of the disparity map I_{LD} followed by the estimation of the Laplacian. The Gaussian filter acts as a smoothing operator and the Laplacian generates zero crossings required for performing the desired edge detection. The Gaussian filtering in our case can be effectively used to reduce or eliminate the extraction of subtle changes in depth, which provide low perceptual value in the comprehension of scene depth.

The zero crossings of the LoG filter can then be used to locate edges, which are in fact depth discontinuities. The advantage of the LoG filter over other edge detection methods is that it can be trivially used to select as a depth discontinuity those pixels that are either on the dark or light side of a discontinuity, that is to select locally the foreground or the background object in the disparity map. As we discussed earlier, in our algorithm the lighter side of a depth discontinuity is of interest, since it represents the boundary that has higher disparity and therefore is closer to the viewpoint. To do this, we detect all zero crossings in the response of the convolution of I_{LD} with an approximation of the LoG filter, that is $\nabla^2 G(x, y) * I_{LD}(x, y) = 0$, and extract as foreground pixels the side of the depth discontinuity where the LoG-convolved image has negative values. This procedure can be very efficiently implemented by applying a binary thresholding operation at the zero crossings.

The set of detected pixels is then morphologically thinned using a combination of the thinning technique described in [132] followed by the Holt's [49] staircase removal algorithm to further eliminate "unnecessary pixels" (i.e. pixels that can be removed while reserving edge connectivity) in diagonal edge directions. Thinning



(a) (b) (c) (d) (e)

FIGURE 5.2 *Figure (a) shows a portion of a disparity map, with brighter pixels representing higher disparity values. We compare the response of standard edge detection methods in a small sample area, marked by the blue square in Figure (a), enlarged in Figure (b). The edge pixels of the bright part of the sampled area have to be detected. Figure (c) shows the response of the Sobel edge detector. The detected edge is broken, and also edge pixels are erroneously detected on the darker side of the depth discontinuity. Figure (d) shows the result obtained by applying the Canny edge detector. The edge is continuous, but the detected pixels are selected both to be on the dark and the light side of the discontinuity. Figure (e) presents the result of the method described here, which is based on the Zero Crossings operator. The foreground side of the depth discontinuity is accurately detected, without any errors. Equivalent results can be obtained from other areas of the disparity map.*

and staircase removal strive to eliminate edge information until edges are of unit thickness. While the discarded information, in our case coded in image pixels, may be imperceptible by visual inspection of monoscopic images, it is an important step for successive processing, such as vectorization, to succeed.

A simple iterative contour extraction procedure is then used to convert the edge pixels into connected components. This is trivially achieved by detecting end pixels (i.e. pixels that have only one neighbor) and then recursively following the connected pixels until no more pixels remain to process for the current pixel set. Each extracted connected component is represented by a set of points $p(x, y)$, with x and y being their coordinates in the 2D coordinate system of the image. To further enhance the output of the detected contours, prior to rendering them, very small lines can be removed using a user defined threshold that is related to the amount of points in the connected components.

5.3 Contour Simplification and Vectorization

The detected contours will usually appear to trace objects and form long continuous lines that turn and curve unnaturally to follow depth discontinuities, resembling more closely the result of a mechanical plotter, rather than a human sketch.

To create a more appealing set of lines that appear less mechanical and computer-generated, we detect points of high curvature along the contours (i.e. corners) and recursively subdivide the lines at those points, effectively creating a set of non-overlapping disconnected segments that represent the initial contour, similarly to how humans simplify long continuous lines when drawing.

While the detection and extraction steps of foreground pixels that make up line segments are sufficient to directly synthesize an image reminiscent of a sketch, the raster representation of the extracted contours is limiting in a number of ways. The points describing each contour may be unnecessarily dense, leading to both decrease of performance as well as increase of storage requirements. In addition, existing algorithms for stroke stylization and rendering are usually based on parametric curve models [48] and therefore are not applicable. Finally, the raster representation cannot be reliably scaled and therefore transferring the stereo drawings on paper or other media may lead to loss of quality.

To overcome these limitations, we describe a simple method for simplifying and vectorizing the raster contours extracted. Raster-to-vector conversion is a widely used technique for converting pixel-based representations into geometrical primitives, finding great utility in digitization of line drawings [103] and optical character recognition [117]. A hard constraint imposed on our vectorization method is that pixels describing the contour before the vectorization should be converted to geometric primitives, without changing their position in image space. This constraint is motivated by the requirement to use only those extracted lines that are visible in both views. Using fitting or approximation techniques that displace contour points even by a unit of only one pixel is inappropriate, because the new contour may contain pixels that inadequately fall into occluded regions, a situation that was strictly prevented in the feature extraction step. Therefore, we convert a raster edge to a vector by considering its pixels to be control points of a spline curve. Control points are removed from the spline curve using a user-defined parameter $r \in [0, 1]$, which provides a percentage of the total number of control points (N_c) to be removed from the spline. The removal is performed uniformly by preserving the first and last control points and removing $(N_c - 2)r$ intermediate control points. As the simplification factor r increases, the stylization of the produced stereo drawing increases. This process satisfies the constraint of preserving the original edge pixel locations as the control point coordinates and, as described next, enables the generation of the second view using these splines.

5.4 Generating the Second View

Performing the same processing, i.e. contour extraction, simplification and vectorization, in the second view to obtain the other component of the sketched stereo pair is possible but unnecessary, since the extracted lines are, by the algorithm's design, visible in the other view as well. The disparity map, which provides us with the point correspondences between the two image planes, can be readily used to warp the control points of the splines from the reference to the second view.

In Figures 5.3(a) and 5.3(b) the resulting consistent stereo pair before simplification is shown, while in Figures 5.3(c) and 5.3(d) the same contours are shown after simplification.

5.5 Results and Discussion

It is important to point out that handmade sketches, as well as the ones produced by our system, may not encode sufficient monocular depth cues for a viewer to appreciate depth from one of the two stereo components alone. The communication of depth in sketching is greatly dependent on monocular depth cues, e.g. size and occlusion, and ambiguities may arise that cannot be explicitly resolved by just a single

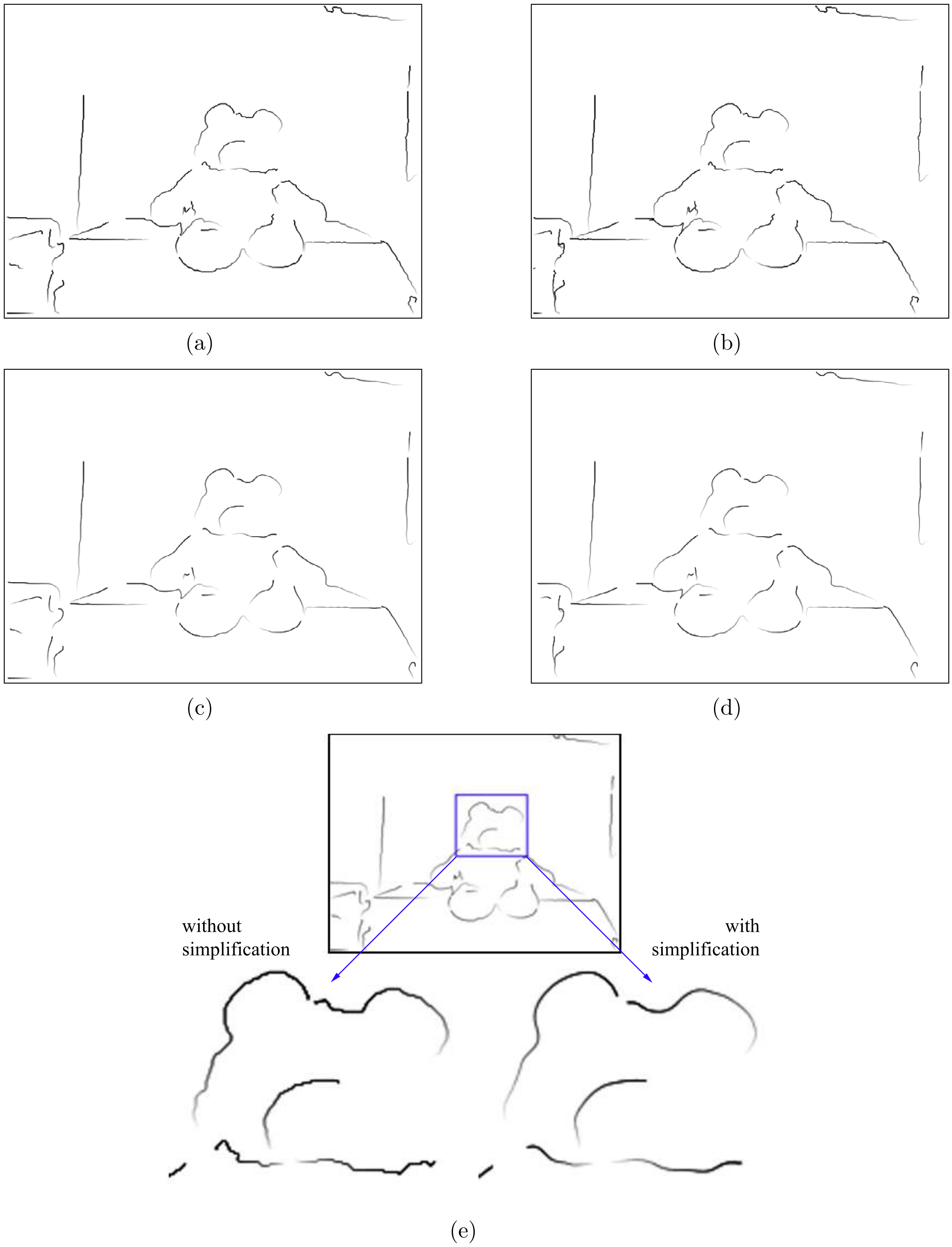
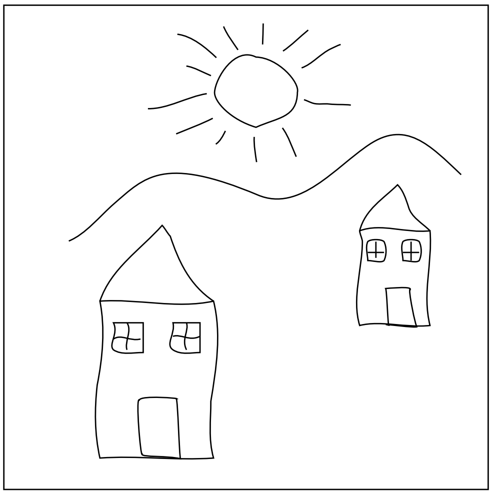


Figure 5.3 *An automatically generated stereoscopic drawing of the "Brown Teddy" dataset, shown in Figure 4.2. Here, Figures (a) and (b) show the left and right stereo components of the consistent drawing generated by our algorithm, and Figures (c) and (d) show the same stereo drawing after the procedure of line simplification, described in Section 5.3, has been applied. By maintaining a lower control point density in the second stereo pair, strokes become smoother and have fewer corners. This can be clearly observed by comparing the enlarged strokes shown in Figure (e), without and with simplification applied.*

view sketch. However, when the two images are viewed stereoscopically, the fused stereo image makes scene depth information apparent by providing binocular depth cues. As an example, consider the case of a single component being viewed from the children's drawing shown in Figure 5.4. The visual system uses size constancy in order to resolve the scene's depth. It is common to perceive the house on the left being closer to the viewer, while the one on the right being further at the back. In addition the position of the sun cannot be determined from a single view of the drawing alone, but may be assumed to be far away behind the mountains. Viewing the stereoscopic pair of drawings, however, it turns out that the house on the left is further behind than the one on the right, but much larger in size, and the sun is hanging in space in front of the mountains and slightly behind the houses. This example clearly demonstrates the power of the stereoscopic medium and shows how stereoscopy can disambiguate and clarify depth.


(a)

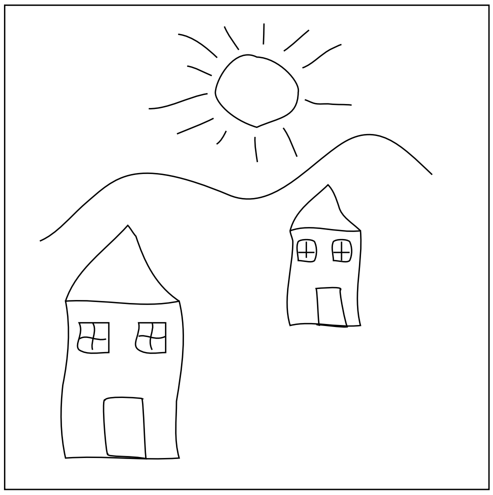

(b)

FIGURE 5.4 *A stereoscopic version of a children's drawing. The two stereoscopic components, with the left shown in Figure (a) and the right one in Figure (b), do not encode sufficient monocular depth cues for the evaluation of depth.*

The stereoscopic sketching algorithm presented here can be used to produce intermediate novel views that are also consistent, lending itself to applications that superimpose outlines on novel views. Novel intermediate views along the stereo baseline can be easily generated by scaling the disparity vector $\vec{d}$. These views can also be stereoscopically fused.

The pseudocode summarizing the stereoscopic drawing algorithm described is presented in Algorithm 1 and the contour extraction is presented in Procedure 2. An example stereo drawing produced with our algorithm is shown in Figure 5.3. In this example the contours are converted to tapered strokes of varying intensity that roughly simulates the pen's pressure. These contours could also be filtered by more elaborate line simplification and stylization algorithms, drawing knowledge from recent line simplification techniques such as [106, 6]. A second dataset and the result of applying the stereoscopic drawing algorithm described here is presented in Figure 5.5.

Algorithm 1: Stereoscopic Drawing Pseudocode.

input : Disparity map of the left view: I_{LD}
input : User-defined threshold: T
input : User-defined Minimum length of extracted contours: $minContourLength$
output: Depth discontinuities binary image: I_{DD}

initialize;

`/* Extract a drawing for the left stereo view */`

I_{tmp} = `convolve`(I_{LD}, LoG);
I_{DD} = `threshold`(I_{tmp}, T);
contours = `extractContours`(I_{DD}, $minContourLength$);
$splines_L$ = `convertContoursToSplines`($contours$);
`stylizeSplines`($splines_L$);

`/* Generate a drawing for the right stereo view. */`

$splines_R$ = `warp`($splines_L, I_{LD}$);

Procedure `extractContours`(*Image* I_{edge}, *Int minContourLength*)

```
input  : A binary edge image: I_edge
input  : Minimum length of a contour (measured in pixels): minContourLength
output: An array of contours: contours

contoursArray = NULL ;
/* Thin binary edge image, until features cannot be further thinned.
   The thinning function returns the number of pixels it has removed
   from the input image.  The thinning operations are performed
   in-place, meaning that the pixel buffer is directly manipulated.
   */
ApplyThinning = true ;
repeat
    ApplyThinning = thinning(I_edge);
until (ApplyThinning == false) ;
ContourExtracted = true;
repeat
    foreach (pixel ∈ I_edge) do
        if (pixel == endpoint) then
            contour = create contour;
            /* Since each line has 2 end points the followLineFrom()
               procedure removes pixels from I_edge that have been
               inserted to a contour, so that the line is not processed
               twice.  A recursive function can also be implemented to
               return each single pixel belonging to the contour as it
               traces it.                                              */
            contour = followLineFrom(pixel);
            if (contour.length() >= minContourLength) then
                contoursArray += contour;
                ContourExtracted = true;
            end
            continue;
        end
        ContourExtracted = false;
    end
until ContourExtracted == false ;
```

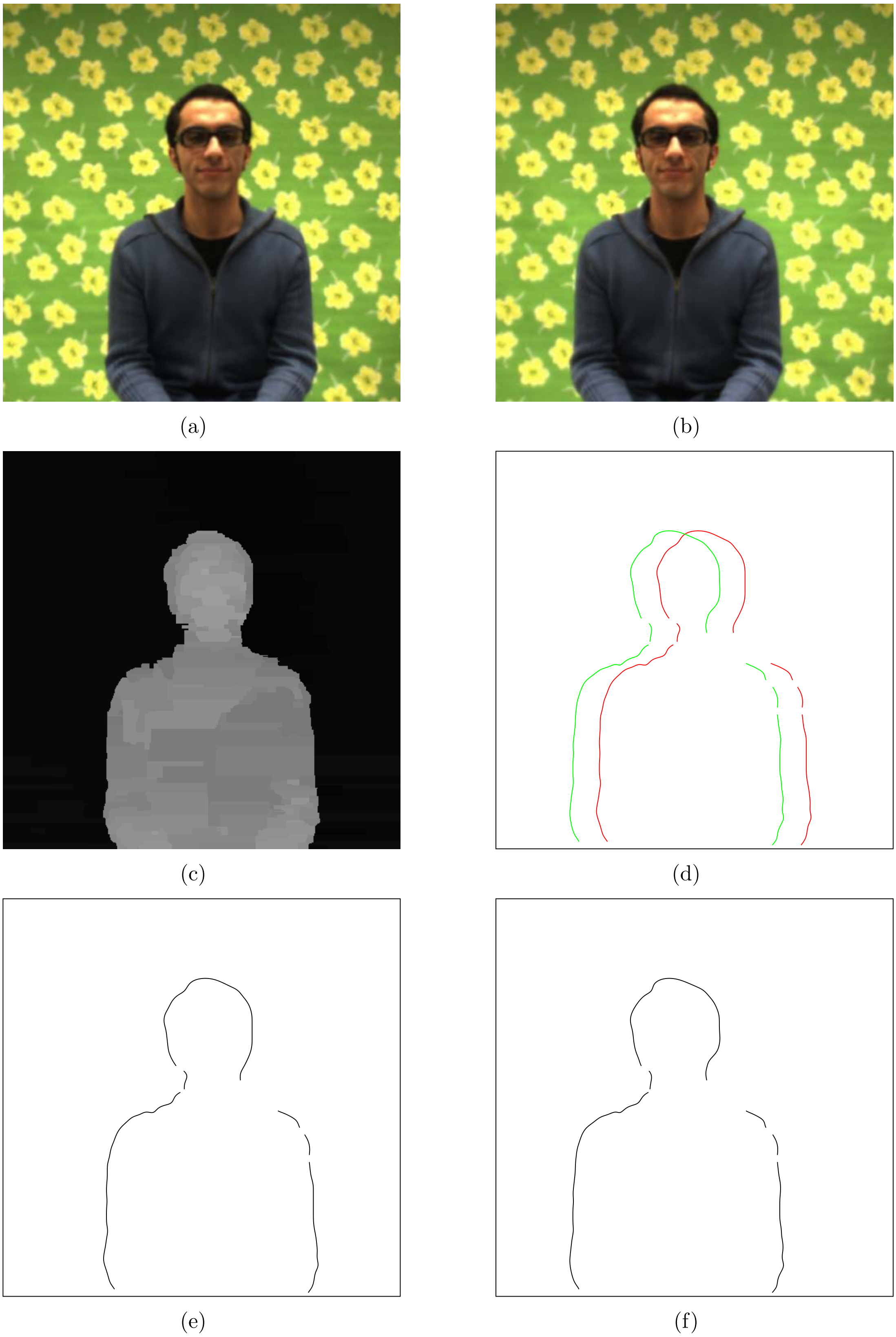


FIGURE 5.5 *Automatically generated stereoscopic drawing. Figures (a) and (b) are the left and right input stereo components, Figure (c) is the respective disparity map generated using the pixel-to-pixel stereo matching algorithm [10]. Figure (d) is the resulting stereoscopic drawing rendered as a red/green anaglyph, and Figures (e) and (f) show the left and right stereoscopic result rendered using a uniform black outline for parallel viewing.*

Chapter 6

Stereoscopic Stylization

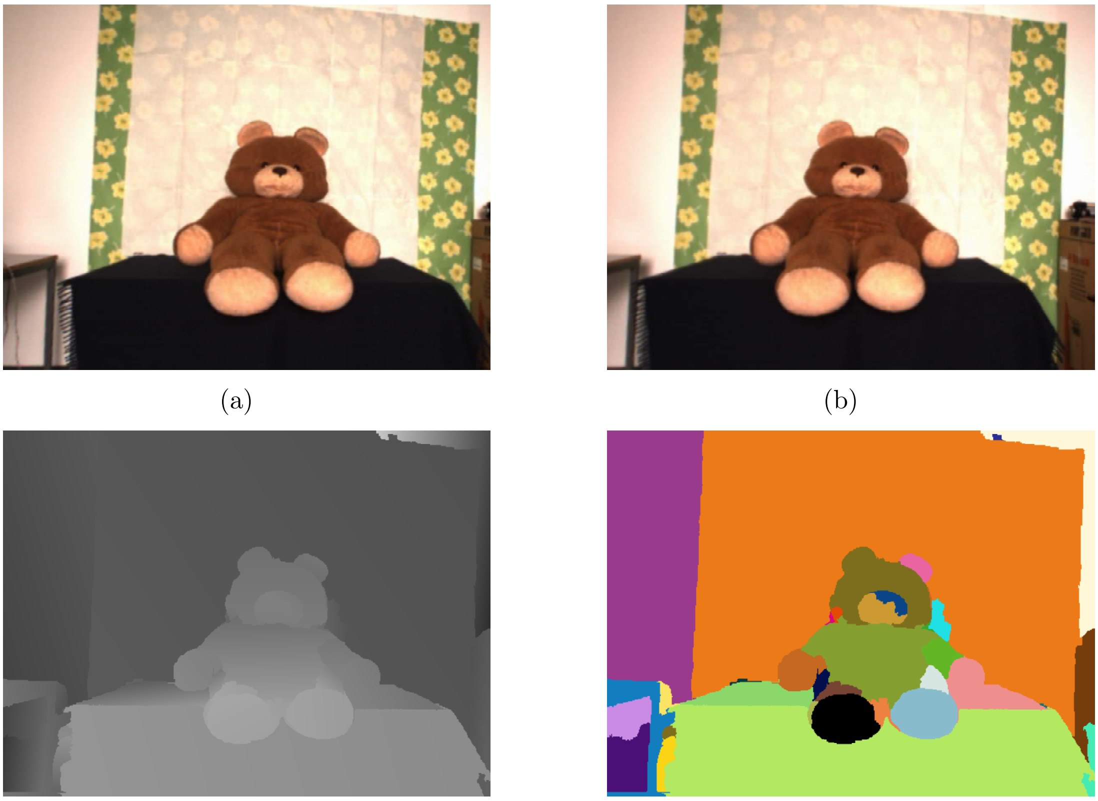
In recent years, DeCarlo and Santella published a series of papers [28, 89, 90] describing a stylization technique that uses color image segmentation, focusing mainly on the use of eye-tracking data to guide the stylization process and evaluate its results. Their techniques, as well as the work of Gooch et al. [39] and successively various others [20, 8], provide solid evidence that computer vision techniques can be used in place of, or in conjunction with, traditional computer graphics algorithms to generate artistic-looking images. The need for controlled enhancement of images specifically targeted to various aspects of the human visual system and perception points in the direction of using methods *to understand image features from a perceptual standpoint* and not at the low-level of signal processing alone. The output of blackbox NPR algorithms has been proven too sterile for such a demanding task and these algorithms are phased down in light of new methods. The design of these new methods promotes human factors, which are after all central in NPR. This set of NPR techniques was therefore a natural evolution of the field at a conceptual and theoretical level, which also had an obvious role in the intertwining of computer vision and computer graphics algorithms. This trend of understanding features in images and then enhance them is now becoming common practice in NPR with much success.

Along this line of work, we present a method that can be used to generate stylized stereo imagery. The algorithm presented here tackles a set of problems that are associated with multiview processing. The spatial structure of an imaged scene is first extracted, and this information becomes the basis for the stylization of the input stereo pairs. On a basic level, the method demonstrates that it is possible to interchange certain computer graphics algorithms with computer vision methods without altering neither the stereoscopic pipeline nor the guidelines that are used in the work presented throughout this dissertation.

The stereo stylization method is not restricted to provide only the consistency required in stereo NPR, but it is further extended to incorporate a distance-dependent rendering mechanism that is motivated by traditional level of detail (LOD) techniques [65] and perception-based image synthesis and associated experiments [122]. This extended version of the algorithm is an example of how depth can increase the perceptibility of selected features, by abstracting and stylizing portions of the images according to their distance from the viewer. The viewer is no longer driving the selection of the appropriate level of detail, but he is rather presented with a composition in which the picture-maker guides the viewer's perception in the third dimension. In our work, we bias the depth perception of the viewer by enhancing certain monocular depth cues (i.e. texture and silhouettes) simultaneously to providing binocular depth cues via the consistently stylized stereo pictures.

6.1 Preprocessing

Like in the previous methods we use stereo vision techniques to analyze real stereo image pairs. We utilize the region-based stereo matching algorithm proposed by Bleyer and Gelautz [12], which does not only estimate disparities of the given scene, but it additionally provides as a byproduct a secondary $2\frac{1}{2}$D representation of the scene. This auxiliary buffer encodes the spatial extents of the different depth layers of the scene, in image space. This representation can be thought of as the outcome of a depth segmentation process and it can be utilized in many different ways for both monoscopic and stereoscopic NPR. Much like how G-Buffers have been previously used in traditional NPR [108, p.183], the disparity map and the depth layers buffer can be considered to be the depth and the ID-buffer, respectively. This is because the disparity map can be used to infer a depth map and the depth layers suggest a rough object segmentation of the scene. The output of this stereo algorithm is both a dense disparity map and a depth layers map, an example of these two representations is shown in Figure 6.1. A schematic overview of the proposed method is shown in Figure 6.2. It must be noted here that the depth layers map used in the subsequent stereo stylization procedure could also be provided by the user interactively. This would enable the user to semantically separate scene objects and group them into different depth layers, rather than rely on a segmentation based on low-level image features. A major advantage of these semantically segmented scenes is that the user would then have more control over the stylization parameters on a per object basis.



(a) (b) (c) (d)

FIGURE 6.1 *An example output of the segmentation-based stereo matcher [12]: (a) the left image, (b) the right image, (c) the calculated dense disparity map and (d) the depth layers map.*

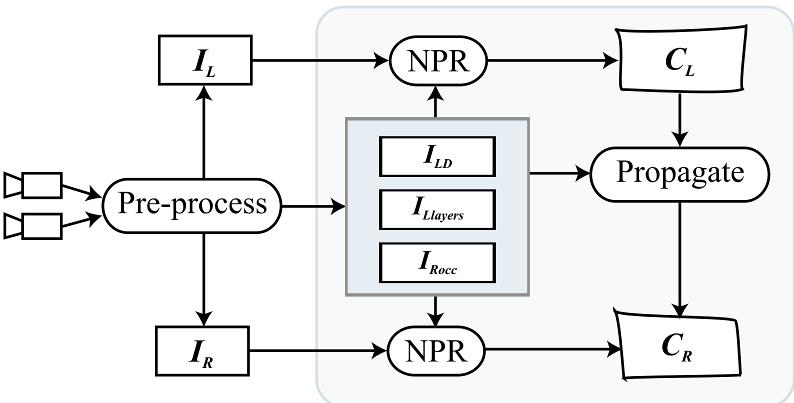
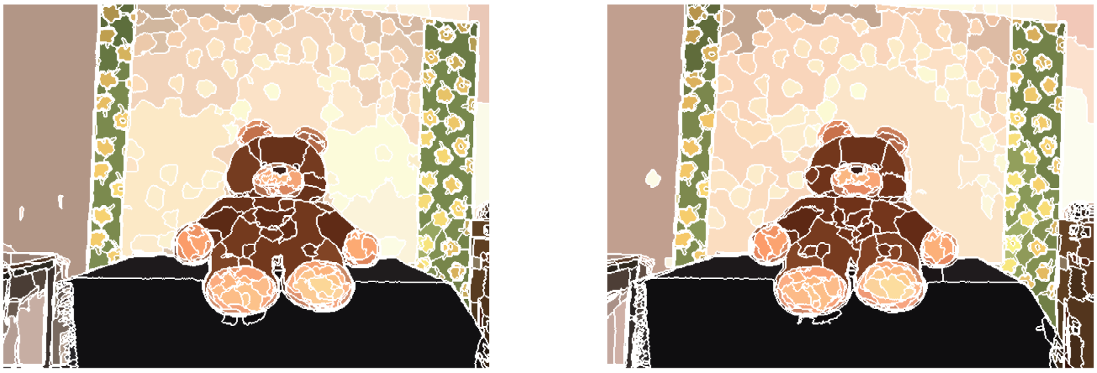


FIGURE 6.2 *The general pipeline for stereoscopic stylization. First the disparity I_{LD}, layers $I_{Llayers}$ and occlusion I_{Rocc} maps are extracted. The reference view is first stylized (C_L) and the result is propagated to the second view and combined with the stylized areas defined in the occlusion map to produce an accurately stylized second view (C_R).*

6.2 Basic Stereoscopic Stylization

When color segmentation algorithms are applied individually to the images of a stereo pair, the resulting segmented images are very likely to exhibit deviations in the shape and color of the segmented regions. To illustrate this shortcoming, we have applied color segmentation individually to the left and right images of a stereo pair, which are shown in Figures 6.1(a) and 6.1(b), respectively. The result of segmenting the two images individually can be seen in Figure 6.3. Notice that even though we have kept constant the parameters of the image segmentation for both images, the result of the segmentation is far from stereoscopically consistent, which can be easily verified even by monocular visual inspection of the image pair.



(a) (b)

FIGURE 6.3 *Individually applying color segmentation with the same parameters on the components of a stereo image pair cannot guarantee to produce stereoscopically consistent segments between the two views. This can be easily observed in the resulting segmentation of the left and right images, shown in Figures (a) and (b), respectively. The white outlines are overlaid only to illustrate where segments have been identified on each of the images.*

One crucial step in generating stylized stereo pairs using color segmentation is therefore to overcome this shortcoming of inconsistent segmentation. This can be achieved by first stylizing the reference view and then using the layer map to warp the texture to the second view. Like in monoscopic NPR techniques we simplify the colors in the reference view by applying color image segmentation. We use an off-the-shelf image segmentation algorithm, based on mean-shift analysis, which is described in detail in [21, 18].

Initially, the reference view is segmented on a per layer basis, so that generated segments never cross over depth discontinuities described by the outer borders of a depth layer. The color value of each pixel per segment is then replaced by the mean color of all pixels belonging to the same segment. In addition, a step that reassigns isolated pixels, i.e. pixels that have a low number of neighbors (in 8-

connectivity), is used to smooth out the boundaries between neighboring segments. Segment boundary smoothing is performed internally on each layer; pixels on the boundaries of segments that are also boundaries of the layer they belong to are not reassigned. This prevents from smoothing out the layers themselves, which would cause depth discontinuities to be shifted from one layer to another, with the potential risk of generating artifacts later when generating the second view.

6.3 Filling in Occlusions

For each depth layer in the layer map we can then warp the contained stylized segments of the reference view to the geometry of the second view to generate most of the latter. This is trivially done by warping the layers themselves, since the texture of the segments is contained. This procedure alone guarantees that the texture of the layers in the reference view will be consistent with the warped texture in the second view. Nevertheless, occlusions in the reference view prevent the generation of a complete second view and therefore occlusions have to be specifically handled. Even though these regions are not visible from the reference view and therefore any type of texture could be applied, the fundamental constraint of texture continuity, discussed in our framework earlier (see Chapter 4), requires that suitable texture is synthesized for these regions.

We first detect these occluded regions in the geometry of the second input view by subtracting the resulting image of the warping operation from the second view itself, as illustrated in Figure 6.4. The difference between the two images is used to define an occlusion map I_{Rocc} that will guide the controlled texture synthesis procedure for these regions in the second view.

FIGURE 6.4 *The occlusion map (rightmost) that defines the regions (marked with red) that need to be stylized in the second view is constructed by taking the difference of the warped second view (middle) and the original second view (leftmost). Small isolated regions of a few pixels are merged with neighboring segments.*

The color segmentation algorithm that was used to stylize the colors of the reference view is used with the same parameters, only within the regions of the occlusion map (I_{Rocc}) in the geometry of the second view. This yields texture for the occluded regions that is similar to the surrounding warped texture, however without necessarily being continuous. To improve the perceptual continuity of the texture locally in these occluded areas, we merge each occluded segment to its most similar neighbor. For every occluded segment S_{occ}, we find the most similar neighboring segment S_{best} among all neighboring segments S_n by minimizing the following objective function:

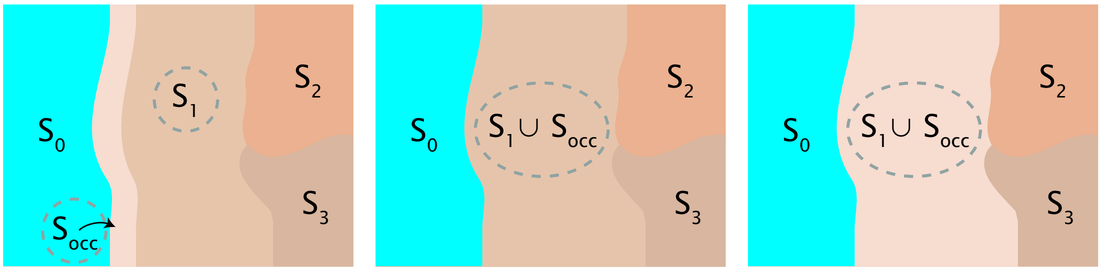
$$S_{best} = \underset{S_n \in S}{\operatorname{argmin}}(d_{RGB}(S_n, S_{occ}) + \ell) \tag{6.1}$$

where the term d_{RGB} is the normalized Euclidean distance in the RGB color space and ℓ is the normalized length of the shared border between the two segments S_n and S_{occ}. S is the set of neighboring segments of S_{occ}. The merging score calculated using Function 6.1 has to be smaller than a threshold T_m. This threshold is provided as a constant, which is iteratively reduced internally by the algorithm until occluded segments are merged to their neighbors. The neighboring segment S_{best} is then chosen as the segment which S_{occ} will be merged to. Merging of the segments is the union of spatial extents of the two segments, and the color of the new merged segment S_M is the color of S_{best}. The resulting stylized stereo pair using this basic stylization procedure can be seen in Figure 6.5.

(a) (b)

FIGURE 6.5 *The final result after applying the basic stylization technique that treats the stereo components uniformly. Notice the preserved consistency across the image pair and the continuous texture in the second view.*

Even though it is possible to assign the color of S_{occ} to S_M or take the average of both segments, we found that the best results were obtained by disregarding the color of the occluded segment. This preserves the texture continuity between the non-occluded segments S_{best} and their other neighboring segments prior to the merging. Another reason motivating the assignment of the color of the warped segments to the occluded ones, and not vice versa, is that color would have to be back-propagated to the reference view for every warped segment that has been merged in the second view, which is an unnecessary additional step. In addition, we found that if the occluded segment provides the color information of the new segment, it is very likely that the new segment may become perceptually discontinuous with its other neighbors, especially if the segment was merged with a marginal score. This concept is illustrated in Figure 6.6.



(a) (b) (c)

FIGURE 6.6 *An example set of segments S propagated from the reference view to the second view via warping is shown in Figure (a). The merging procedure will merge the occluded segment S_{occ} to S_1, as shown in Figure (b). It would also be possible to assign the color of S_{occ} to S_1. However, as it can be observed in Figure (c), in certain segment configurations assigning the color of the occluded segment to the warped segment may cause the warped segment's (S_1) color to deviate from the color of its other neighbors (S_2 and S_3).*

For the merging operation a user-defined threshold T_m provides a mechanism to control how similar the best matching segment can be, before it can be merged. This threshold is provided because there are cases in which segments in the occluded regions should not be merged, and have their color reassigned, for instance when a completely occluded object is revealed. Such a segment will not be merged to the surrounding segments because of high color dissimilarity.

We reprocess these occluded segments that have high color differences and thus could not be merged to neighboring visible segments, in order to assign them to neighboring depth layers. This effectively extends the depth layers in the second view to include occluded regions, by extrapolating existing depth values of the layer to these segments. The criterion used to assign the occluded segments to depth layers is to find the depth layer with the smallest average disparity along the shared border with the occluded segment and to consider the occluded segment part of the planar depth layer. This means that the segment will become part of the depth layer that is locally further away from the viewpoint than any other surrounding layers.

An advantage of the segment merging operation lies on the assignment of the occluded segments to depth layers and not only on the visual continuity of the second view, which was the primary motivation. Since layers represent planar surfaces over which disparity varies smoothly, by extending them over the newly merged segments and extrapolating depth values over them, we can obtain a dense disparity map for the second view with the occlusions filled in. The second disparity map can be used to do inverse image warping and is useful when generating intermediate novel views.

6.4 Distance-Dependent Stereoscopic Stylization

The approach described above is rather straightforward, but provides limited control over the stylization result. Even though the images are consistently stylized, they are treated uniformly and the significant information of scene depth is not utilized in any other way apart from generating the second view. In the evaluation of their work with eye-gaze directed stylization, Santella and DeCarlo [90] specifically point out that the effectiveness of NPR can be increased by meaningful abstraction and they show that this can be achieved by varying the detail of the abstracted images according to where their users are fixating with their eyes.

In our stereoscopic system we incorporate the idea that objects closer to the viewer in the natural world have normally higher resolution, and more detail can therefore be distinguished than on objects located further away. We also assume that objects closer to the viewer are of more interest to him. These two assumptions converge into the design of an algorithmic texture synthesis that accentuates the monocular depth cue of texture gradient of foreground objects and attenuates it for objects that are further away.

To achieve this we apply non-uniform stylization across the input images by using the various depth layers of the scene. The key here is to modulate the segmentation process by making its parameters a function of the distance of the surface to be segmented to the viewpoint. To meet the design requirement of "closer-sharper" and "farther-rougher", we abstract closer surfaces less than distant ones, by representing them with more segments. The described distance-dependent NPR algorithm is closely related to the concept of view-dependent level of detail selection [65, p.104].

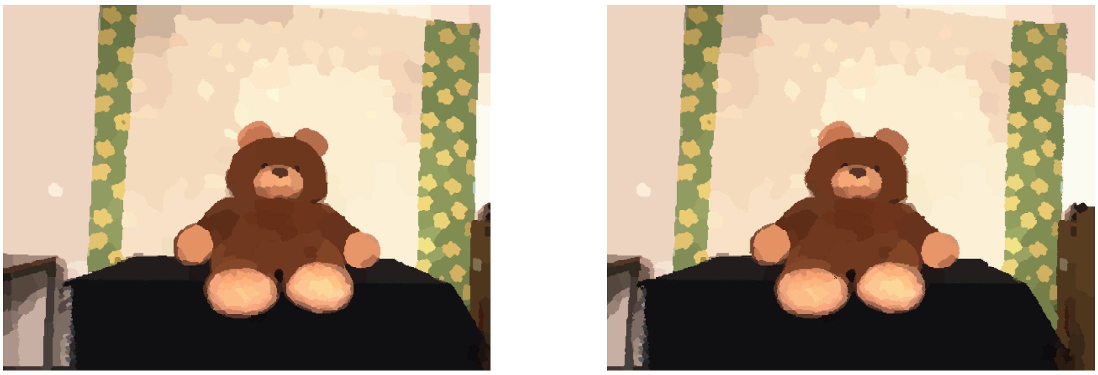
The feature (h_r) and spatial (h_s) bandwidths[1], as well as the minimum region parameter M, of the mean-shift-based segmentation algorithm, can be used to control the granularity of the texture across the different depth layers. Small values of spatial bandwidth combined with small values of feature bandwidth provide a finer segmentation. As the two parameters increase, the resolution of the segmentation

[1]The parameters h_r and h_s of the mean-shift color segmentation algorithm denote the radii of the windows used to compute the offset of the mean vector from the center of that window, in the LUV color space and the image's lattice, respectively.

decreases leading to rougher color stylization. To apply a distance-dependent stylization, we let h_r be slightly smaller than h_s and scale both parameters by a factor equal to the normalized average depth of the segment currently processed. Depth values are normalized in the range of minimum and maximum depth present in the whole scene. As depth increases, and thus segments have smaller disparities, h_r and h_s increase to provide the desired "farther-rougher" and "closer-finer" combination of style in the final images.

To stylize the reference view we use the same procedure described in the case of the basic stylization algorithm. However, we now segment each depth layer with the adaptive segmentation parameters, as described above. According to our previous discussion, occluded regions cannot be readily segmented with the adaptive procedure, since depth values are not initially associated with them. We use the same procedure as with the non-adaptive stylization technique to first assign depth values of neighboring layers to these regions and then proceed to performing the adaptive stylization of these regions, as we have done with the rest of the segments.

The result of adaptively stylizing segments according to their distance from the viewpoint can be seen in Figure 6.7.



(a) (b)

FIGURE 6.7 *The final result of adaptively stylizing segments according to their distance from the viewpoint. Notice how the feet of the teddy bear have much greater detail than the background wall.*

6.5 Outlining

Line is an important factor in image comprehension and, in the context of stereoscopy, it can further assist the viewer to separate the various depth layers. Following the principles of consistency, in stereo imaging we have devised a method to create strokes along certain parts of dominant contours of scene objects. These strokes usually represent parts of silhouettes and creases of objects that are visible in both stereoscopic views.

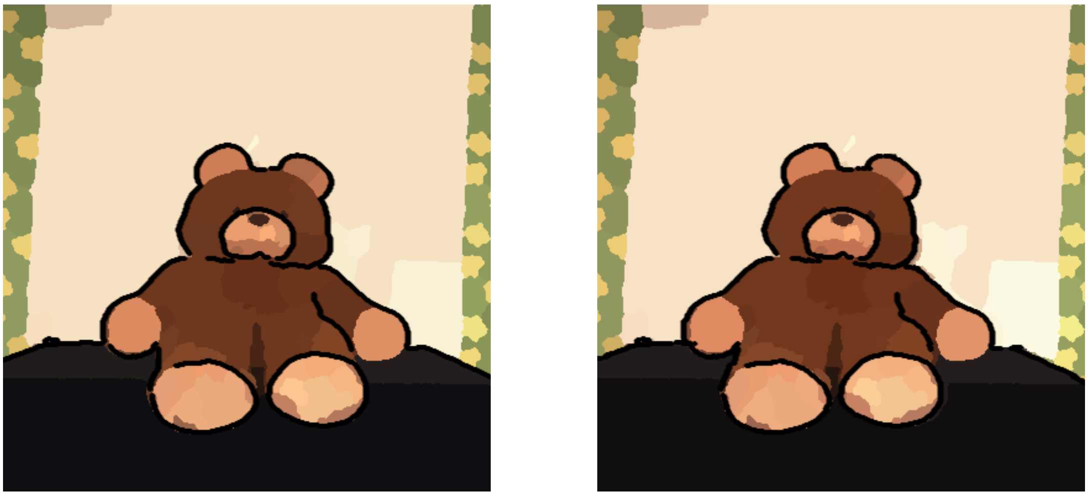
We construct an edge image using the stereoscopic drawing algorithm described in Chapter 5. We also construct a second edge map by tracing the boundaries of the depth layers found in the layer map. The first image provides a set of lines that can be readily used to stroke foreground features of the scene. However, this image is very sensitive to artifacts in the disparity map and also provides by design short lines that are more relevant for a drawing or a sketch than for making complete outlines. For the stylized images that resemble cartoons, produced by the previous segmentation-based stereo algorithm, a more continuous and less sketchy line would be more adequate. The second edge map that essentially is constructed by tracing the depth layer boundaries may include inadequately outlined features, such as background depth layer outlines, or outlines that produce clutter rather than clarity. We make use of the best features of both edge maps. We first label the endpoints of all lines in the extracted edge image using the stereo drawing algorithm in the geometry of the reference view. We take advantage of the depth layer boundaries here to connect lines that belong to the same depth discontinuity that runs along the boundary of a depth layer. Furthermore, we also use the stereo drawing to remove extraneous edge segments that would otherwise be present, if the outlines generated by the layer map were kept intact. This provides a combined set of lines that can also be warped from the reference to the second view in order to generate a consistent stereoscopic outline. This outline can be laid over the stylized stereo pairs to elucidate depth differences in the final stereo rendition.

The density of the lines present in the final edge map can be controlled by a user-defined parameter that provides the maximum distance along a boundary that two edge endpoints may connect. Additional procedures incorporated in the stereoscopic drawing algorithm, such as simplification and vectorization, can be used to further filter the resulting depth edges.

Figure 6.8 shows the final stylized output with the stereo drawing algorithm applied to the “Brown Teddy” dataset. Figure 6.9 shows the result of using the stereo drawing algorithm in combination with the depth layer boundary tracing method described above.

(a) (b)

Figure 6.8 *Figures (a) and (b) are the left and right components of a stylized rendition of the "Brown Teddy" dataset, respectively. Depth edges that were computed by the stereoscopic drawing algorithm are marked with black thin tapered strokes.*



(a) (b)

Figure 6.9 *Figures (a) and (b) show the stylized left and right images of the "Brown Teddy" dataset, respectively. Dominant contours are outlined with a thick black line, similar to those used in cartoons.*

6.6 Results

We have tested our algorithm with various real image datasets. Apart from the self-recorded “Brown Teddy” dataset, we have also stylized the “Venus” dataset of [93], shown in Figure 6.10.

Figures 6.10(a) and 6.10(b) show the original left and right components of the stereo image pair. This scene has a mixture of textured and untextured surfaces, which are split into layers (Figure 6.10(c)) and the respective disparity map extracted by the stereo matching algorithm is shown in Figure 6.10(d). The left stylized view is shown in Figure 6.10(e), and the warped right view before stylizing occlusions is presented in 6.10(f). Example results of the combined stylization and outlining algorithms applied on the “Venus” dataset are shown in Figure 6.11.

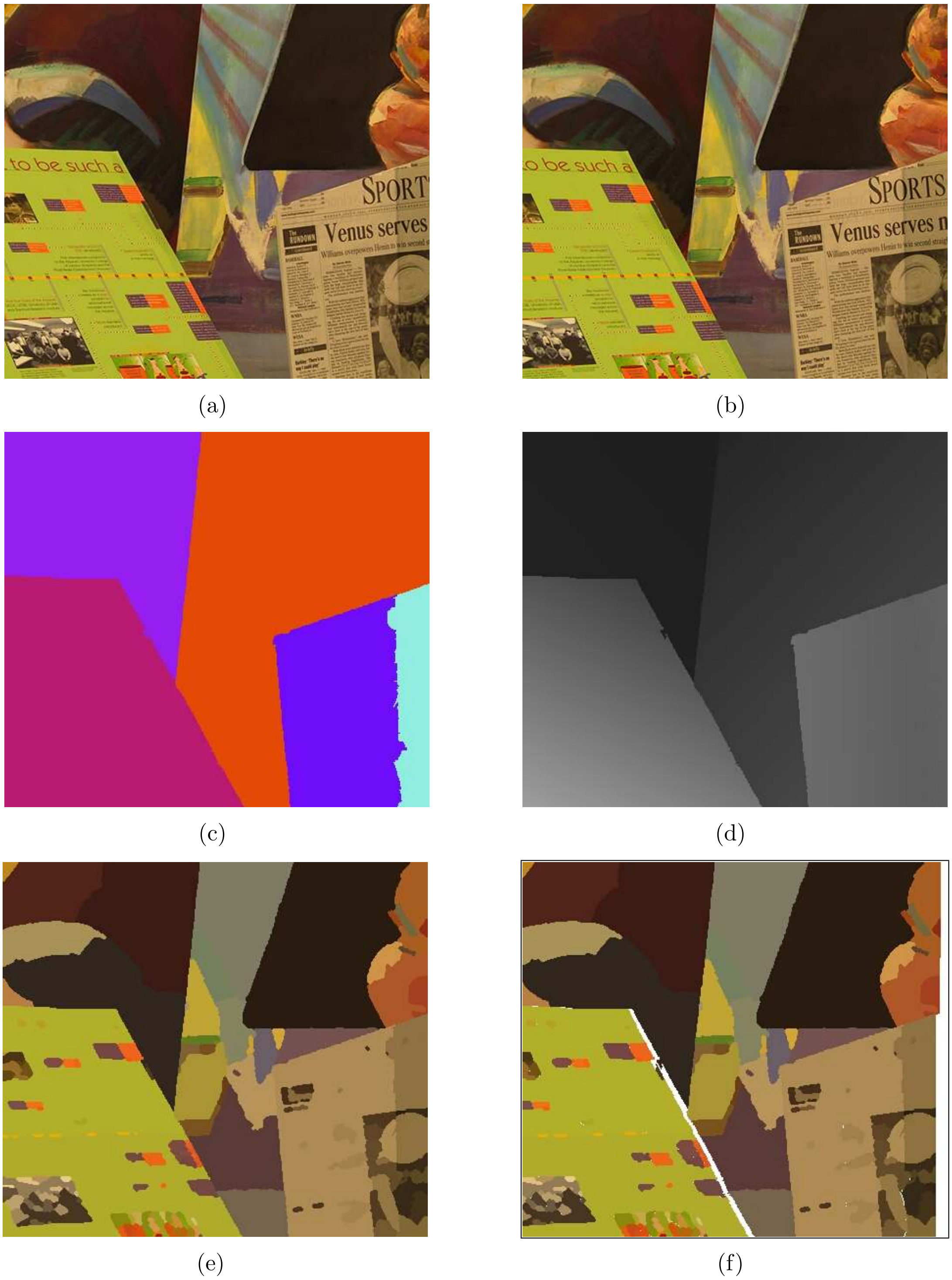


FIGURE 6.10 *Stereoscopic stylization of the "Venus" dataset. (a) Left image. (b) Right image. (c) Layer map of the left image. (d) Disparity map of the left image. (e) Stylized left image. (f) Warped second view, without stylization of occlusions (marked white)*

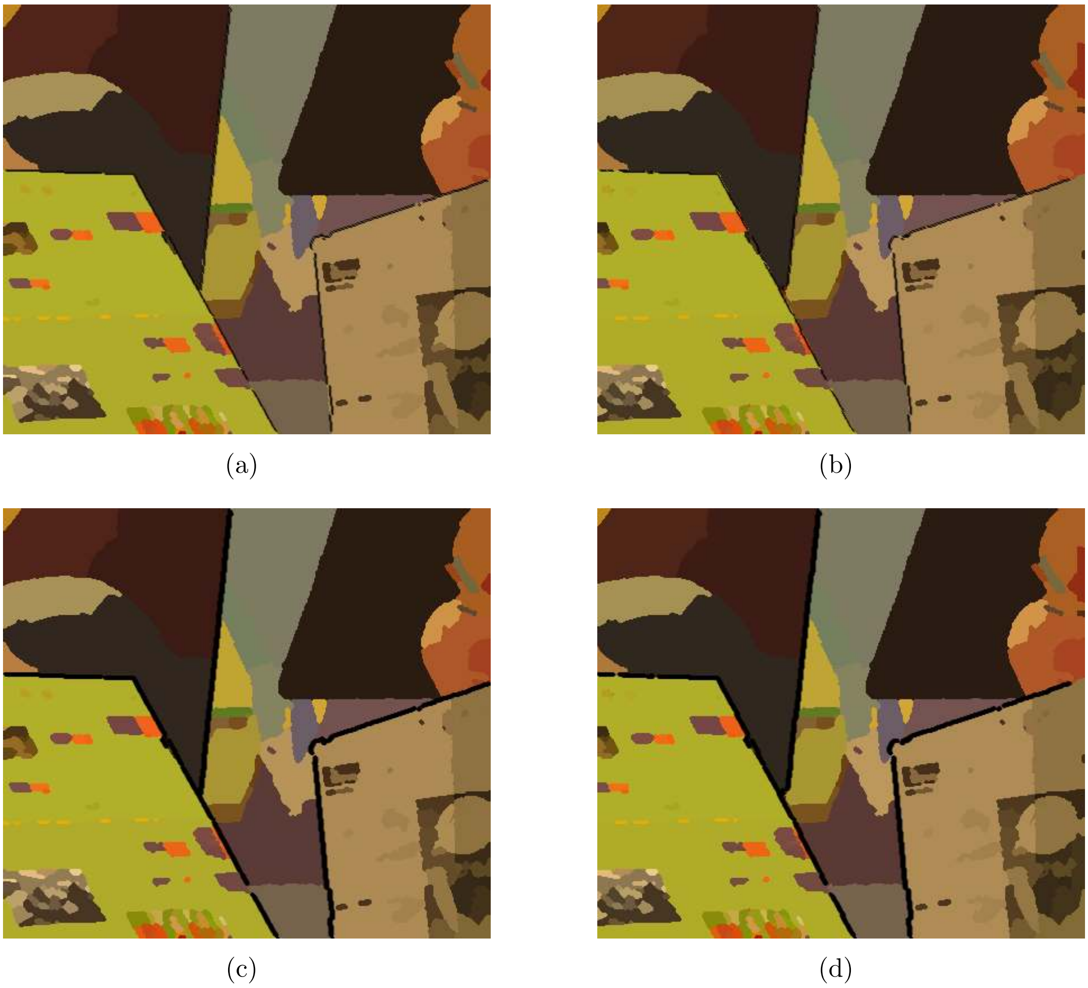


Figure 6.11 *Constant thickness outlining of dominant edges overlaid on stylized "Venus" dataset. In Figures (a) and (b) a thin outline is used, while in Figures (c) and (d) the left and right stylized components are outlined with thicker lines. Lines clarify only depth changes, while texture discontinuities are not highlighted.*

Chapter 7

Stereoscopic Painting

One of the most difficult artistic stereo techniques is stereoscopic painting, both when executed by hand or simulated with a computer. It requires a high level of artistic merit combined with technical expertise. As we have extensively discussed in Section 2.3, the small number of artists that have taken up the task of creating stereo paintings by hand were faced with many technical and perceptual difficulties. To better appreciate the requirements for an image-based algorithm simulating stereo painting, we have identified these problems (e.g. feature correspondence) in the analogue domain, and we now map them into an algorithm that can be used to generate stereoscopic paintings with a computer.

Creating pleasing stereoscopic content requires artwork that effectively communicates the third dimension by means of adequate stimulation of binocular vision. Therefore, stereo artists strive to suppress mistakes in the artwork that lead to binocular rivalry [11]. Particularly, stereo painters that aim to produce static color stimuli preserve across the stereo components the intrinsic properties of the depicted scene objects, such as form, size, color and luminance.

Maintaining consistency of these characteristics between the two projections is not only time consuming, but it may also impose physical constraints for an artist. Thus stereo artwork shifts from being a familiar means of artistic expression to a creative task that also requires considerable technical knowledge. Stereo painters have used a variety of techniques to overcome these technical issues (i.e. preserve the viewpoint and colors' consistency). Some have used careful preliminary stereo drawings, while others have employed reference photographs. Furthermore, we observe that stereo painting does not become less of a demanding task in the digital domain. Digital stereo painters are still required to spend a considerable amount of time on repetitive tasks when using standard 2D image editing and synthesis software. They have to ensure that consistency is preserved manually, since these applications are not targeted for stereoscopic content generation and thus lack appropriate stereo image editing and manipulation tools.

Considering that our algorithms are based on stereo images as an input, our methods are analogous to photographically-assisted stereo painting, in which artists use photographs as a reference. Our strategy to build a relationship between the left and right input stereo images and successively exploit it in a synthesis procedure can also be applied to stereoscopic painting. This suggests that:

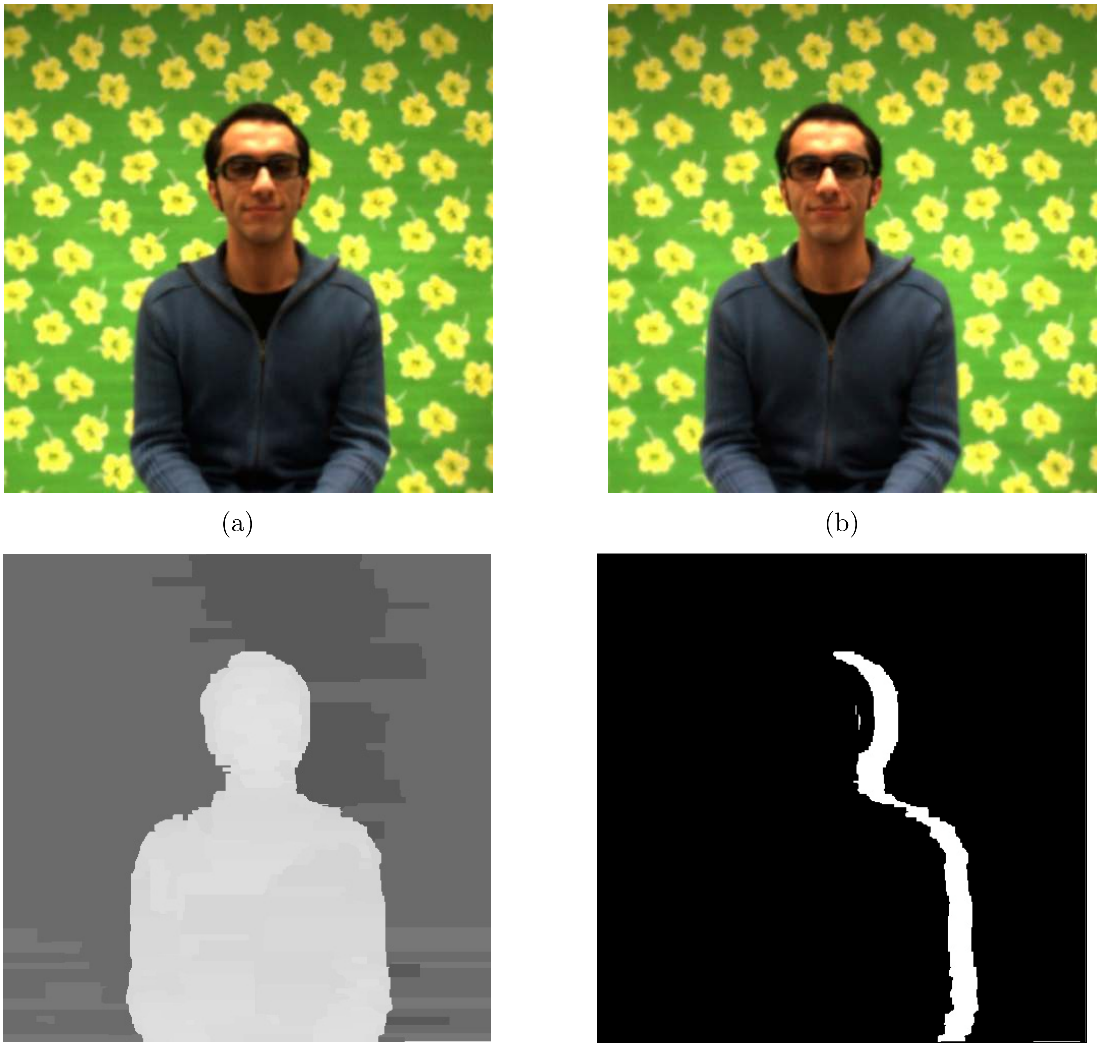
- we can preserve the intrinsic properties of objects depicted in the two stereo components by exploiting their similarities,
- we can preserve consistency within occluded and non-occluded regions in each of the components by identifying and exploiting the dissimilarities between the two stereo components,
- the speed of synthesizing stereo paintings can be increased by generating most of the second, slightly dissimilar, stereoscopic component using information from the first view.

In the following, we show how consistent stereo paintings can be generated using stroke-based rendering.

7.1 Stereo Painting by Image Warping

For a given stereoscopic image pair with I_L and I_R the left and right components, respectively, as shown in Figures 7.1(a) and 7.1(b), we use the respective disparity map I_{LD} (see Figure 7.1(c)) calculated in the geometry of the left view to identify occluded regions of the scene in the right view. Since the disparity map provides a pixel by pixel correspondence to the right view, it is sufficient to use image warping to reproject pixels of the left view into the right. Any remaining pixels in the right view that cannot be mapped could be considered to represent the projections of invisible scene points from the left view. These occluded pixels are encoded with a value of 1 into a binary occlusion map I_{Rocc} for the right view, as shown in Figure 7.1(d). We associate this map with the right view and not with the left one, because it will be later utilized as a mask when painting the right view. Pixels in the occlusion map with a value of 1 are considered as being unmasked pixels, while those with a value of 0 are masked. The painting simulation is applied only in unmasked pixel regions rather than the whole view, thus improving the performance of the overall stereoscopic synthesis.

We first apply a painterly simulation algorithm in I_L to generate the left canvas C_L, based on Hertzmann's [47] curved brush strokes algorithm of multiple sizes (see



(a) (b) (c) (d)

FIGURE 7.1 *Input stereo pair to the painting algorithm. Figures (a) and (b) are the left and right components, and Figure (c) shows the disparity map extracted using the pixel-to-pixel stereo matching algorithm of Birchfield and Tomasi [10]. In Figure (d) the occlusion map for the right view is shown. Areas marked white are not visible from the left view.*

Appendix A for a more detailed description of the modified painterly algorithm). Using the unmasked pixel locations in the occlusion map I_{Rocc}, we paint directly in the corresponding area of the image of I_R into the resulting right canvas image C_R. To complete the right view, we use the disparity map I_{LD} to warp C_L atop the partially completed C_R. The stereoscopic pipeline used for this algorithm, as shown in Figure 7.2, is similar to that used in the stereoscopic stylization algorithm (Section 6), but the *NPR* procedure is now replaced by the painterly algorithm and the *propagation* of style is performed by image warping.

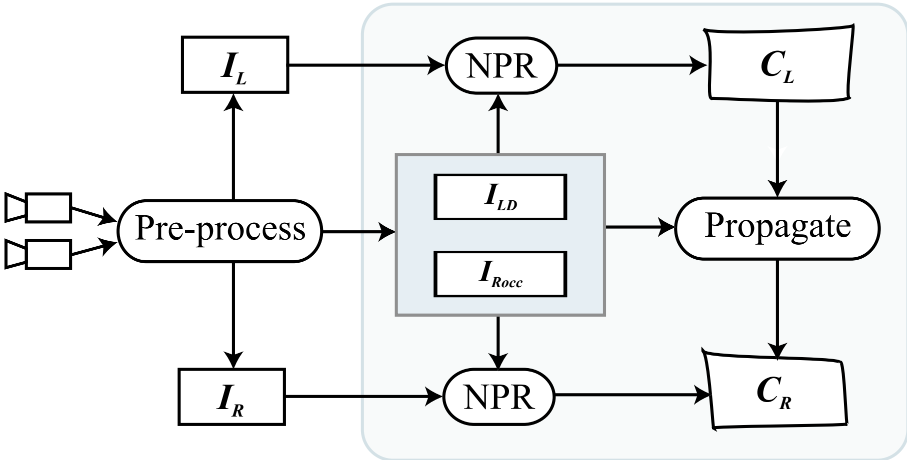


FIGURE 7.2 *Processing pipeline for stereoscopic painting by image warping.*

In our approach, the masked regions in the occlusion map (marked with black in Figure 7.3(a)) denote positions in image space from which brush strokes may not be *initiated*. However, after the first control point of a stroke is placed in an unmasked region, successive control points of the stroke may be placed anywhere, including masked regions, according to the stroke planning procedure, as described in Section A.2. Therefore, strokes can be thought of as emanating from unmasked into masked regions, as shown in Figure 7.4(a). The advantage of this approach over requiring all control points to be within unmasked pixel locations is that the texture generated by the strokes will better blend with the surrounding texture, as well as the texture propagated from the other view by image warping.

In addition, an unmasked region may not form an area where sufficient information is present for the stroke planning algorithm to generate strokes. For instance the unmasked area may be too small to include more than a couple of control points, thus the stroke termination criterion of stroke length (e.g. of at least 4 control points) will prevent the planning of the stroke.

Other problems arise from common errors in disparity estimation, such as small holes in the disparity map or the effect of foreground object “fattening” that block-

(a) (b)

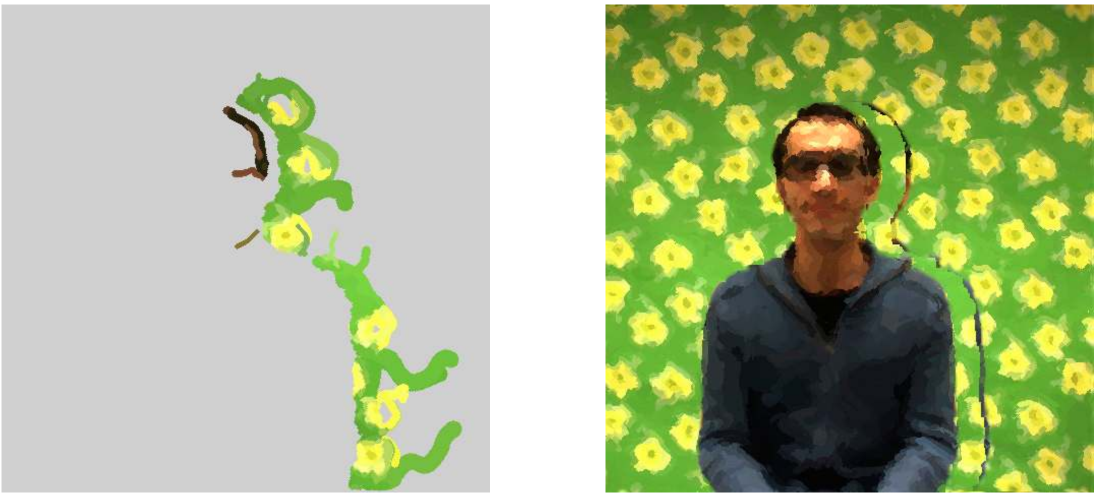
FIGURE 7.3 *On Figure (a), the original occlusions are marked with white, while on Figure (b) the occlusion map is expanded by morphological dilation to allow better treatment of occlusions by the painterly algorithm.*

based stereo matching algorithms are known to produce. Small holes can be filled in by interpolating neighboring reliable disparity estimates. Inaccuracies along object boundaries in the disparity map will cause pixels to be erroneously transformed while propagating paint, via image warping, from the reference to the second view. An example of this problem is shown in Figure 7.4(b).

Because these inaccuracies are usually located around occlusions, instead of generating strokes strictly within the initially identified occluded regions, we expand the unmasked area in I_{Rocc} by applying a morphological dilation, which is analogous of a boolean convolution of I_{Rocc} with a kernel k of size $N \times N$:

$$I'_{Rocc} = k * I_{Rocc} \tag{7.1}$$

where $k(k_x, k_y) = 1$, $0 \leq k_x, k_y < N$. An example occlusion map before and after morphological dilation is shown in Figures 7.3(a) and 7.3(b), respectively. We found that an effective value for the size of the kernel is $N = 2r_{max}$, with r_{max} being the radius of the largest brush stroke that is used in the layered painting process. By expanding the mask by $2r_{max}$ in all directions, texture is generated in the second view for a larger area. This area includes the pixels along the inaccurate object boundary in the disparity map that otherwise may have caused a visible seam of erroneous paint to appear in the second view, as that shown in Figure 7.4(b). The expansion of the unmasked region enables the painting algorithm to generate texture, shown in Figure 7.5(a), that can sufficiently prevent the problematic seams from appearing



(a) (b)

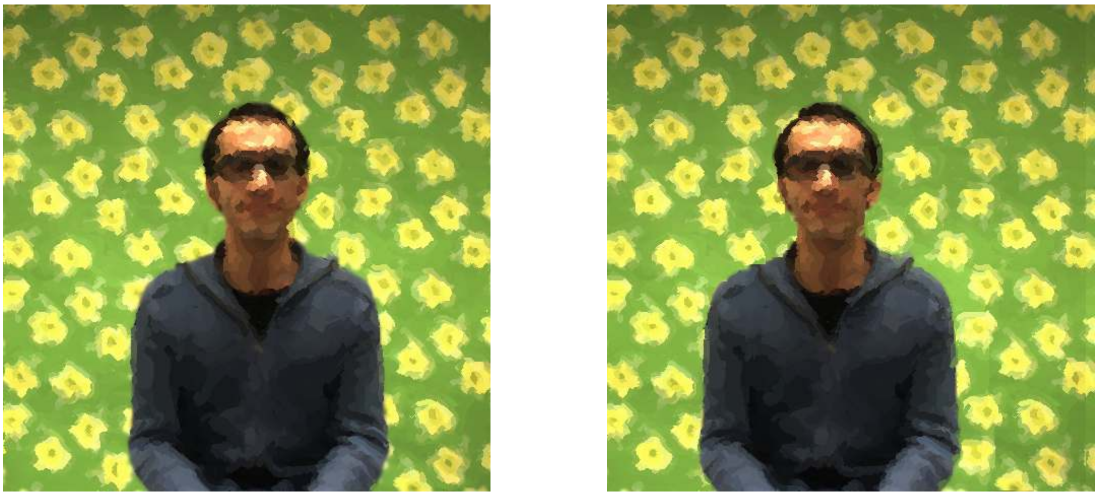
FIGURE 7.4 *The strokes are allowed to emanate from the unmasked pixels in the occlusion map to masked pixels. The result of this constrained progressive painting (with 3 layers) is shown in Figure (a). Inaccuracies in the disparity map, in particular foreground object boundary expansion, produce a right stereo component after image warping that has noticeable defects, as shown in Figure (b).*

(a) (b)

FIGURE 7.5 *After applying a morphological dilation to the occlusion map and then filling in occlusions (Figure (a)), the final painting of the right view (Figure (b)) has no visible seams like the ones present in Figure 7.4(b).*

in the final painting of the second view, shown in Figure 7.5(b).

Applying this stereoscopic painterly algorithm on the input stereo image pair shown in Figure 7.1 yields the stereoscopic painting shown in Figure 7.6. The algorithm applied on the self-recorded “Brown Teddy” dataset is shown in Figure 7.7. Both results are rendered using layers of strokes with radii 8, 4 and 2 pixels.



(a) (b)

FIGURE 7.6 *The final stereo painting generated by using the image warping algorithm, with the errors arising from inaccuracies in the disparity map eliminated.*

(a) (b)

FIGURE 7.7 *Figures (a) and (b) show respectively the left and right painted components of the “Brown Teddy” dataset (see Figure 4.2), using the painterly stereo algorithm based on image warping.*

7.2 Stereo Painting by Stroke Warping

The algorithm described in the previous section is based on the principle of transferring paint from the reference canvas to the second, by warping the paint generated in the reference view. In this section, we present a modification of this algorithm in which style is transferred between the two stereoscopic components by warping the stroke primitives themselves, instead of the paint they deposit on the canvas.

In stereoscopic painting by stroke warping, brush strokes are assigned a unique z value $d_S \in [0, 255]$, which is naively chosen to be the depth value at the first control point of the stroke. We do not follow surface orientation, as the disparity maps we use do not always provide sufficient information for accurate surface reconstruction. We chose to draw the strokes normal to the line of sight at the associated depth value d_S instead, hence a certain amount of cardboarding[1] must be expected.

Since strokes are now rendered at different depths, strokes emanating from occluded regions in the second view will need to be assigned appropriate depth values and warped back to the reference view to preserve consistency. The processing pipeline for stroke based painting is shown in Figure 7.8.

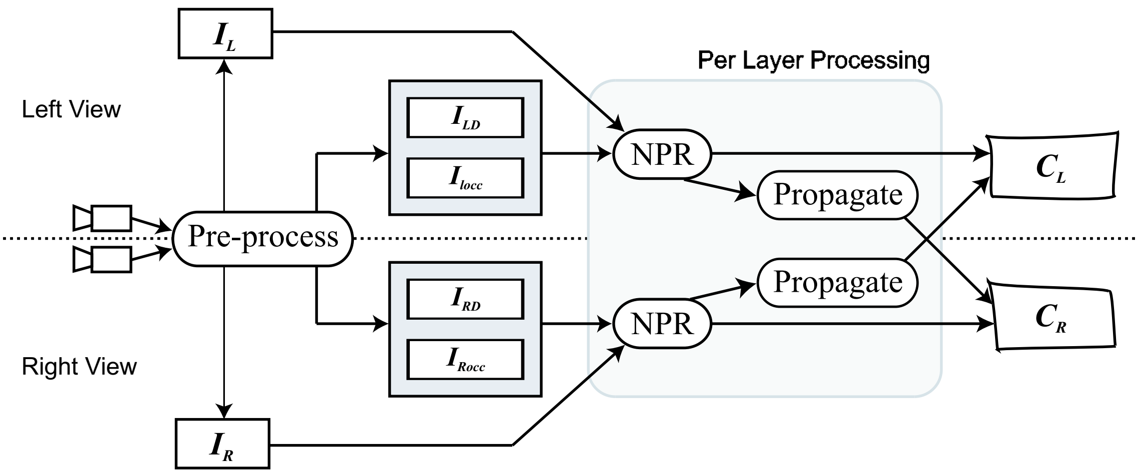
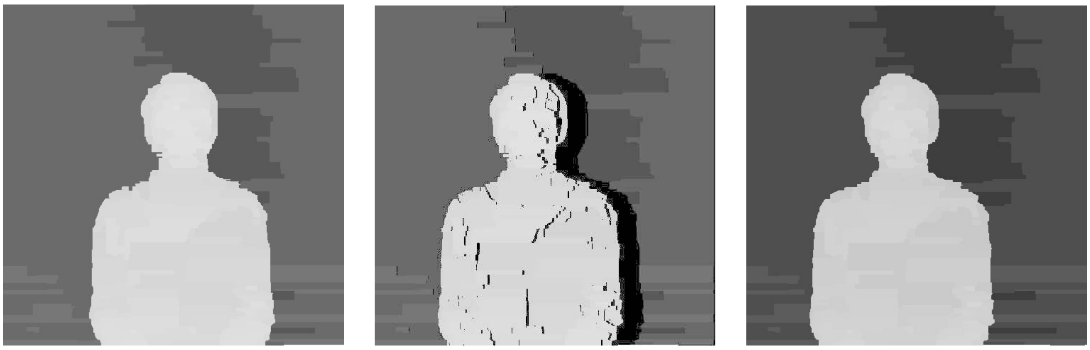


FIGURE 7.8 *Processing pipeline for stereoscopic painting by stroke warping. Strokes generated in each view are warped to the other view per layer to preserve consistency.*

In the image warping technique, the generated strokes always deposit paint behind the transferred paint from the reference view. However, when propagating paint via stroke warping, we retain all strokes and their respective depth values, including strokes generated in occluded regions. This implies that depth values for occluded strokes need to be generated, thus an additional disparity map in the geometry of the second view is required. This disparity map may be provided by the

[1]Cardboarding is the effect of smooth surfaces being perceived as flat cutouts in the stereo fused image.

stereo matching algorithm directly, or the disparity map of the reference view can be warped to the second view and reliable neighboring disparities may be used to fill in occlusions, as shown in Figure 7.9.

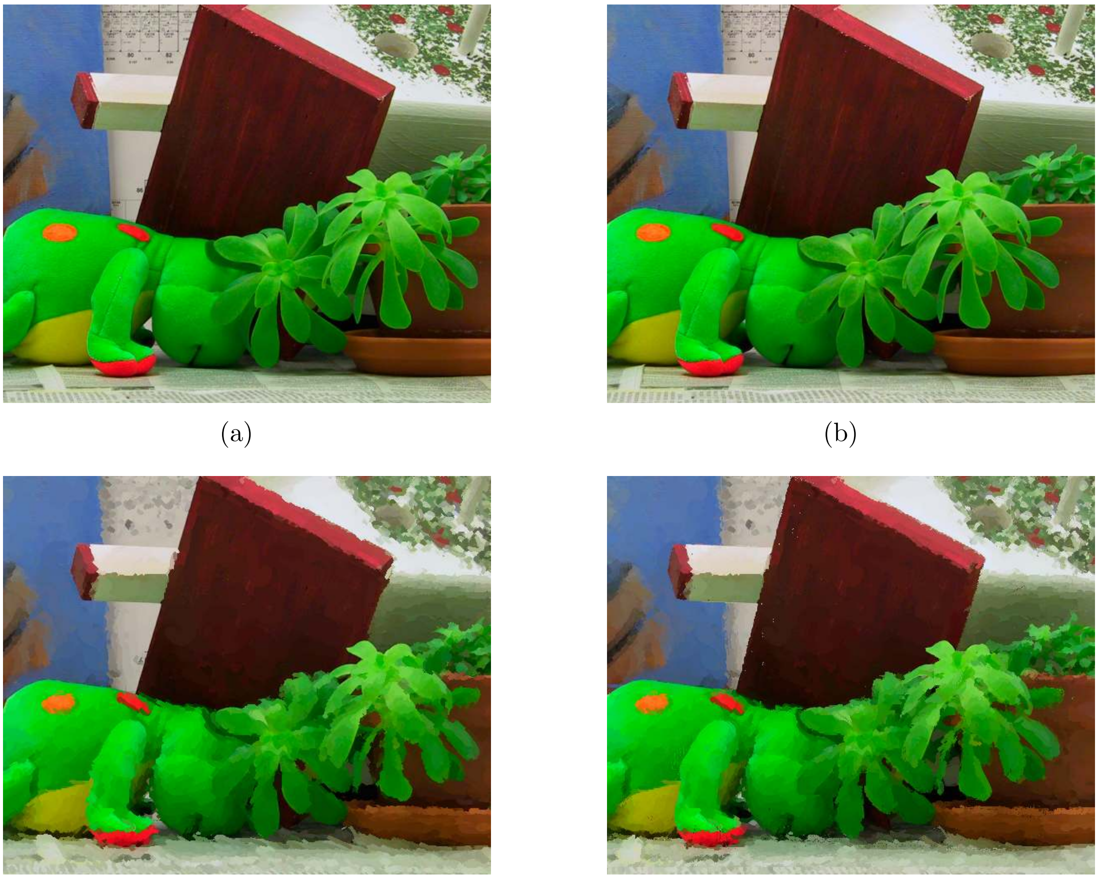


(a) (b) (c)

FIGURE 7.9 *Figure (a) shows the disparity map computed using the pixel-to-pixel stereo matching algorithm [10] in the geometry of the left view. This disparity map is used to infer the disparity map in the geometry of the right view. The left disparity map is first warped to the geometry of the second view, shown in Figure (b). Holes are then filled in by using reliable neighboring disparities to produce a dense disparity map for the second view, as shown in Figure (c).*

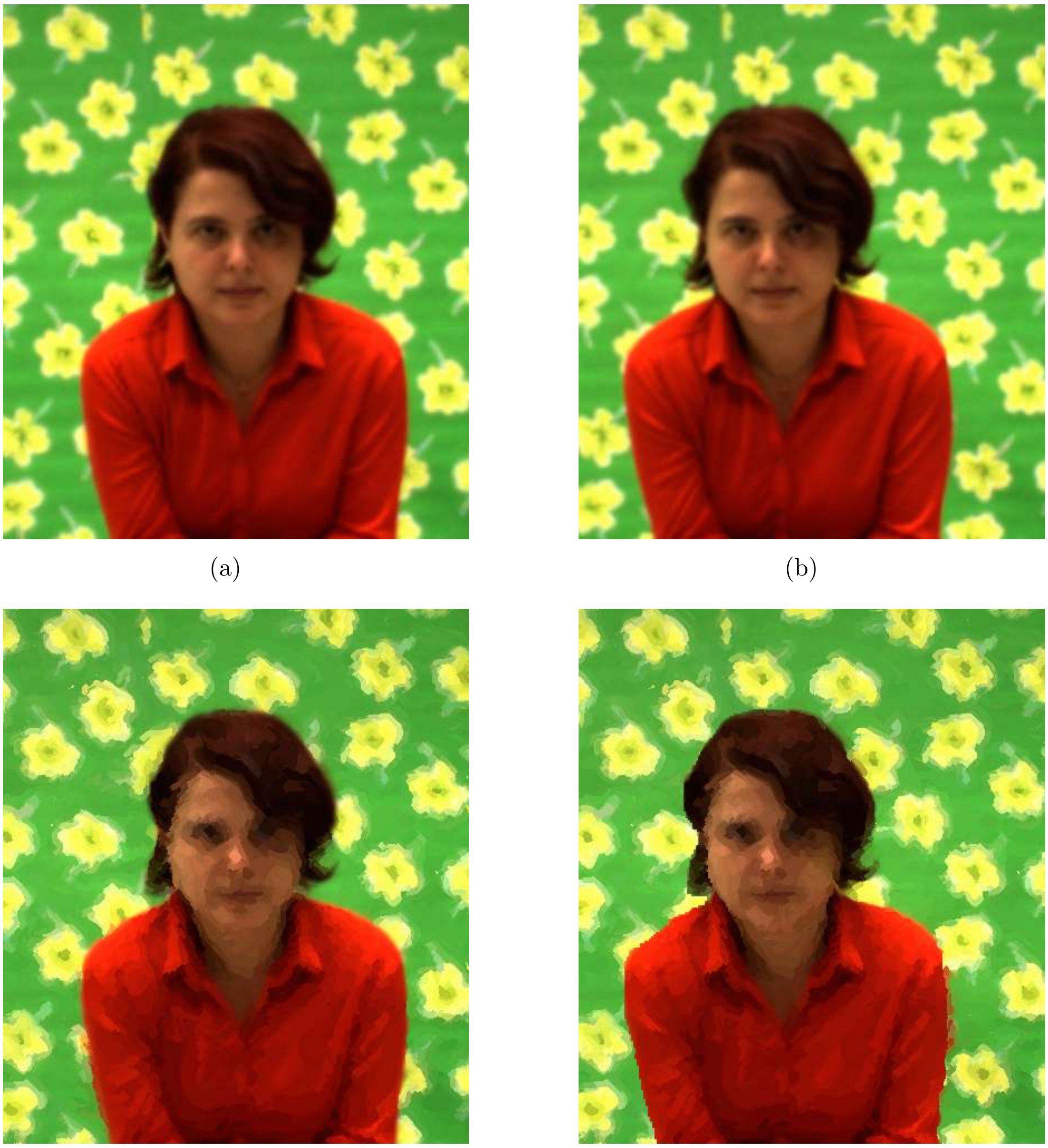
The stereoscopic painterly algorithm is then applied on a per layer basis, progressively from coarse to fine, simultaneously to the left and right components of the stereoscopic input pair. Strokes generated in each of the views to fill in occlusions in the other view are warped back in the respective other view to preserve consistency. This is necessary since strokes emanating from occluded regions need to be present in both views, as we are interested in providing a stereoscopic painting that has consistent structure at all depths.

Example stereoscopic paintings generated with the stroke warping technique can be seen in Figures 7.10 and 7.11. Both paintings are generated using stroke radii of 8, 4 and 2 pixels.



(a) (b) (c) (d)

FIGURE 7.10 *Painted "Teddy" stereo pair, courtesy of Middlebury college. In the top row the original left and right components of the stereo pair are shown and at the bottom their painted counterparts.*



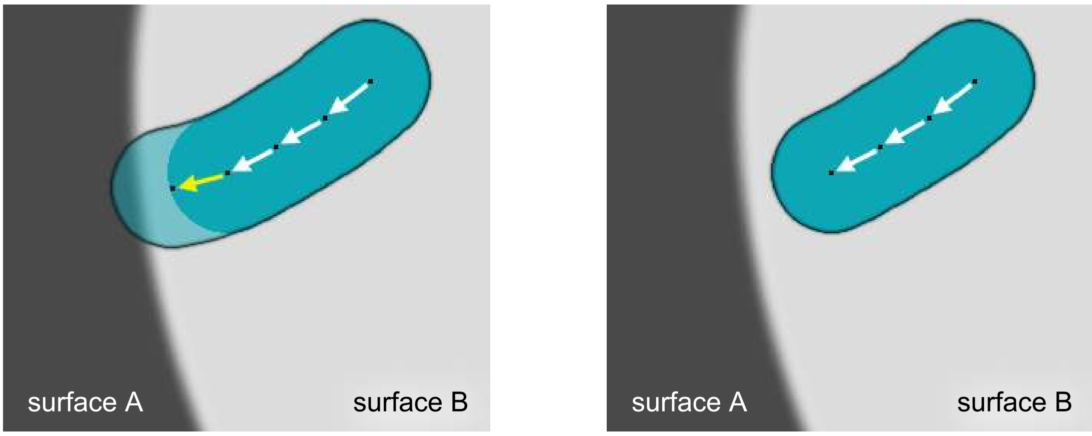
(a) (b) (c) (d)

FIGURE 7.11 *Painted "Girl" stereo pair. In the top row the original left and right components of the stereo pair are shown and at the bottom their painted counterparts.*

7.3 Combining Stereoscopic Drawing with Painting

In multiple stroke-based NPR techniques it has been shown that stroke clipping may be used to preserve salient features of depicted scene objects. A common strategy in stroke clipping is that introduced by Litwinowiz [63], who uses simple edge detection to clip the path of strokes. Similarly, Hertzmann's stroke model [47] accounts for color changes. However, when two objects with similar colors lie at different distances, the algorithm does not have the facilities to treat the two objects separately.

In our framework the availability of the disparity map is essential in that it describes object boundaries. Using depth discontinuities inferred from the disparity maps, as identified by our stereoscopic drawing algorithm, can be used to imitate the artist's concept drawings that are usually created before painting in with color. The main goal of the stereo artist using stereo drawings is to preserve the stereoscopic disparities and lock the workspace within boundaries that should not be overpainted. We use depth discontinuities to clip strokes so that they do not extend to surfaces of different depths, as shown in Figure 7.12.



(a) (b)

FIGURE 7.12 *Figure (a) shows a stroke extending beyond a single surface. In Figure (b), the stroke is clipped against the depth discontinuity, which effectively prevents paint from spilling between surfaces at different depths.*

Additionally, a stereoscopic painting may be overlaid with distinct strokes that visibly trace the boundaries of painted objects, similarly to the way outlines have been used in our stylization algorithm of Chapter 6. The outlining of objects in a stereo composition helps viewers to separate depth layers more easily by giving rise to the monocular cue of interposition. These outlines, as we have extensively discussed in Chapter 5, are generated in the reference view and automatically warped to the second one, posing a significant visual and artistic aid with a minimal computational effort. An example stereo outline is automatically appended to the painting generated by the image warping algorithm in Figure 7.13.

(a)

(b)

FIGURE 7.13 *A black stereoscopic outline generated by the drawing algorithm (see Chapter 5) can be overlaid to the output of the painting algorithm in order to provide guiding cues for separating depth layers more easily. Figures (a) and (b) show the left and right images.*

7.4 Summary

In this chapter, we have presented an image-based stereoscopic painterly rendering algorithm which can turn stereoscopic image pairs into consistent stereoscopic paintings. The algorithm takes advantage of stereo disparities to propagate generated paint from one view to the other. This effectively reduces the computational requirements, since the second view need not be calculated in its entirety.

The method based on image warping utilizes the depth discontinuities in the disparity map to constrain stroke planning, as well as to identify occlusions in order to specifically treat them. Strokes are painted in a random order and the corrective set of strokes filling in occluded regions in the second view is assumed to always be behind paint transferred from the reference view. This technique produces a pair of 2D images that can be fused stereoscopically, but the underlying structure of the painting is unavailable for further processing.

Stereo painting by image warping works well for high fidelity paintings that are refined with strokes small enough to make inaccuracies in the disparity map less apparent to the viewer, by taking advantage of our strategy of extending the unmasked regions in the occlusion map. We then have modified the stereoscopic painterly algorithm to warp strokes instead of the paint deposited by them. This modification enables stereoscopic paintings that are consistent at all depths and motivates the design of a slicing tool that can be used to examine the understructure of a stereoscopic painting, as will be discussed in detail in Section 8.4.

We have finally shown that stereoscopic outlines may be utilized in stereoscopic painterly rendering, either as an algorithmic aid (e.g. to clip strokes) or as stimuli to assist the viewer's visual system in separating the depth layers.

Chapter 8

Techniques for Stereoscopic Interactivity

To interact with the stereo artwork generated with the various algorithms presented in the previous chapters, two modes of interactivity are introduced here and their corresponding supportive user interfacing is described. The first mode of interactivity built into our image-based stereoscopic non-photorealistic rendering system enables users to manipulate the stereoscopic components to adjust the perceived depth of the scene. The second mode provides the observer a set of unique tools for exploring the structure of the automatically generated stereo artwork.

The two interaction methods allow a user to affect the look-and-feel of the artwork in stereo. The interactive interface is very intuitive and easy to use. It provides to non-expert users those tools required to explore the stereoscopic space occupied by the stereo artwork *within* the stereoscopic space itself. By combining interaction techniques of both modes, the artwork can be decomposed or explored by the spectator, while simultaneously maintaining an eye-strain-free stereo display, which further enhances the viewing experience.

8.1 Introduction

Recently, interactive stereoscopic techniques have become popular in 3D virtual and augmented reality applications. Typically, such stereoscopic systems use tracking to identify the position and orientation of the user's head and then they utilize this information to render accurately stereoscopic image pairs of the available virtual geometric objects of the 3D scene. Users may be provided with a wide range of tools to interact with the virtual worlds and can freely move within them, however the complexity of these worlds is limited to the availability of 3D objects. As these systems are primarily based on 3D geometry, while very flexible, they may not be ideal for 2D artists (e.g. painters). In addition, obtaining and maintaining virtual and augmented reality systems is still quite costly and thus less appealing for the end-user (artist or art enthusiast).

Advances in image-based modeling and rendering may eventually enable digital artists to use photographic images instead of 3D models as their raw material. Nevertheless, the rapidly expanding areas of automatic stereoscopic image synthesis and analysis cannot alone lead artists to adopt stereoscopy as an artistic medium, neither their audiences may find the automatically generated content satisfactory. Enhancing interactivity in the process of image-based artistic stereoscopic content generation, as well as visualization, may be a key to the wider use of stereoscopy in arts.

Along this line of investigation, we describe a number of interactive methods and tools that can be used within an image-based rendering system to inspect and interact with digital computer-generated stereoscopic artworks. First, we outline the use of horizontal image translation as a way of manipulating stereoscopic space, while preventing frame cancellation. We then describe an image-based method for rendering stereoscopic cursors and show how the method can be applied to provide a simple stereoscopic pointer, as well as a stereoscopic magnifying glass. Finally, we provide a description of the spatial arrangement of artwork generated in our system, which enables us to provide a special interactive tool that can be used to peel away layers of the artwork which are at different distances.

8.2 Manipulating Stereoscopic Space

Basic interaction with a real three-dimensional scene, using only a single stereoscopic image pair, does not require expensive and complicated-to-setup virtual reality equipment. Instead, standard stereoscopic graphics hardware can be used (i.e. a graphics card capable of stereoscopic rendering and a pair of active stereo shutter glasses). The level of interactivity possible is, of course, limited when compared to complete 3D systems. This can be partially compensated by inferring geometric attributes of the depicted scene objects, without however attempting to fully reconstruct and segment the scene's objects. In our system, we use disparity maps as auxiliary data both by the NPR stereo algorithms, as well as by the interactive methods described in this section.

8.2.1 Frame Cancellation

A common problem when viewing stereo image pairs arises when binocular disparity is incompatible with an overlap cue to depth. The most common example of this is when the frame of the presentation window, within the digital display, perceptually occludes an object that has negative disparity. This means that the object's stereo depth provides the viewer's visual system the sensation that it is located not on or behind the display, but in front of it. As, however, the frame is always at the plane of zero parallax, which coincides with the physical surface of the display, the occlusion of the object by the frame signals to the viewer that the frame is in front of the displayed object. Then the two contradicting depth cues of binocular disparity and overlap are handed down to the visual system which resolves the conflict usually by dropping the information provided by disparity and favoring that of overlap alone, a typical case of depth cue dominance [50]. This conflict is sometimes also referred to as frame cancellation and is tightly related to the breakdown of stereopsis. Various researchers have proposed algorithms that dynamically prevent frame cancellation, mainly by selecting viewpoints that do not let objects intersect with the frame around the display area.

Treating this very problem of conflicting overlap and disparity cues in stereo images and sequences, McVeigh et al. [72] proposed an algorithm that applies horizontal image translation according to a statistical analysis of the disparity information present in the image pairs. Their approach, however, is to always ensure that all perceived points lie on or behind the screen, without considering the tremendous depth sensation provided by scene objects appearing between the user and the physical display. For instance, consider the case of an object's left and right stereo projections that do not intersect the presentation frame but have negative disparities. Perceptually, bringing this object behind the display may not always be as engaging as allowing it to float in space in front of the display. In fact, features protruding the plane of zero parallax give a sense of presence in the perceived 3D environment, while scenes perceptually behind the display provide a feeling of looking through a window.

Ware et al. [123] also provide insight on how to automatically adjust the parameters of a stereo display for optimal stereo viewing. Their algorithm is targeted toward virtual scenes where the scene is generated by the computer and is continuously changing. In contrast, our content is mostly static and our goal is to allow the user to intuitively adjust the parameters of the stereo system in order to bring features of his liking behind, on, or in front of the display. While very similar in concept, Ware et al. [123] perform false-eye separation and not image shifting. Many of the ideas and results of their user studies can be taken into consideration in our case too, however, the practical implementation cannot be adapted. The main reason is that the viewpoints in our case are precalculated and fixed, while most false-eye separation algorithms strive to select the optimal separation between the viewpoints for a given scene and use it to render the two stereo projections from.

In his doctoral dissertation, Wartell [124] discusses various problems that arise when using stereoscopic head-tracked displays and describes fusion control algorithms that can be used to counter them. In our work, the stereoscopic display system is based on static stimuli and not all techniques are meaningful in this context. However, of particular interest is the image shifting technique presented by Wartell, in which the two image projections are translated either closer or further away from each other in order to bring the perceived frustum at a certain distance from the observer.

Bringing these ideas together, we let the user of our stereoscopic system interactively change the separation of the two projections by horizontally translating the two components. At the most basic form, we allow the user to provide input via the keyboard to increase or decrease the separation of the stereo images. We define horizontal image translation as a pair of translation vectors ($\vec{t}_L$ and $\vec{t}_R$), always parallel to the x-axis, whose magnitudes are equal, but their directions opposite ($\vec{t}_R = -\vec{t}_L$).

The two image planes are of the same size ($width \times height$) and, when viewed in our system, they are both centered at $(\frac{width}{2}, \frac{height}{2})$, with initial values of $\vec{t}_L = \vec{t}_R = 0$. A positive value of horizontal image translation denotes that the two image planes, left and right, are moving toward each other, otherwise further apart.

8.2.2 Horizontal Image Translation

We found empirically that in most cases users of the stereoscopic viewing system tend to set a horizontal image translation that perceptually brings scene objects in front of the screen rather than behind it, but only if frame cancellation would not occur. Driven by this observation, instead of always positioning the two stereo images so that $|\vec{t}| = 0$, we adjust the viewing parameters of the system so that an optimal horizontal image translation is calculated by processing the available disparity information of the current image pair. Optimality is considered in regards to the initial goal of preventing frame cancellation.

The algorithm does not set all scene points behind the frame, as other techniques do. Instead it scans the border of the disparity map associated with the reference view of the stereo pair for the maximum disparity value. The width of the border can be set as a user parameter. This maximum disparity value is converted to a displacement D_{max} in image space, and the magnitude of the horizontal image translation vectors, which are then applied to the centers of the images, is set to $|\vec{t}| = \frac{D_{max}}{2}$. This way the pixels around the border with the highest disparity will be brought into the plane of zero parallax and therefore they will be on the surface of the display. This allows a scene to be partially in front and behind the display at the same time, without triggering a disparity-overlap cue conflict. This is because the border scan approach ensures that no features in front of the display are also at the border, therefore objects that are inside the border may freely be either in front or behind the display, depending on their original disparity values and scene structure.

The idea behind horizontal image translation for practical stereo viewing is simple and can also be thought of in terms of a stationary viewer to whom we move the scene closer or farther. Consider a point p in space and its left and right projections p_L and p_R, respectively, as shown in Figure 8.1. If the initial perceived depth of p is in front of the display surface, in which case $\vec{t}_L = \vec{t}_R = 0$ as shown in the leftmost component of Figure 8.1, then to shift this point so that it appears behind the display we can use a positive $|\vec{t}|$, and the resulting perceived depth of p will be as is shown in the middle diagram of Figure 8.1. Finally, if instead of applying a positive horizontal image translation we applied a negative one, then the point would come even closer to the observer, as shown in the rightmost component of Figure 8.1.

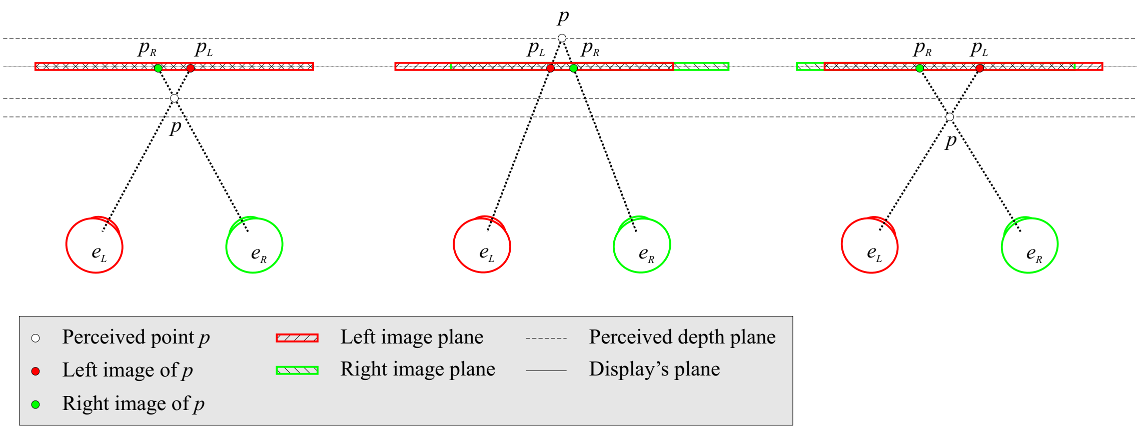


FIGURE 8.1 *Adjusting the parallax by using horizontal image translation. The configuration on the left shows an image pair with $|\vec{t}| = 0$ at the initial state. In the middle a positive horizontal image translation is applied ($|\vec{t}| > 0$) and the point is perceived behind the display. Finally on the right diagram, a negative horizontal image translation ($|\vec{t}| < 0$) results in the point being moved even closer to the observer.*

Based on the image shifting algorithm described above, we further allow the users of our system to interactively select any pixel in the geometry of the reference view, which should be brought onto the plane of zero parallax. If the selected image pixel is i_L and its disparity is D_{i_L}, then we apply horizontal image translation vectors with a magnitude of $|\vec{t}| = \frac{D_{i_L}}{2}$. Interactivity provided via a pointing device, in contrast to the keyboard or automatic initial adjustment of image separation, has two further shortcomings that should be carefully considered. First, as the user interacts with the resulting artwork of the system, without seeing the disparity map, the image plane of the reference view will cease to correspond with the image plane of the disparity map. Care must be taken so that the coordinates of the user's pointer are mapped into the coordinate system of the reference image plane, so that they can be successfully used to retrieve the disparity value of the selected pixel in the disparity map[1].

The second problem is related to the speed of applying the horizontal image translation vectors. Ware et al. [123] performed user studies which are particularly interesting in this context. They reveal that dynamic changes in eye separation should not be rapid, so that the visual system of the viewer can adapt to the new depth information without an abrupt readjustment of the human sensory facilities that could cause them to perceptually exit the virtual world. They report that a low rate of change is an acceptable speed for adjusting the separation of the viewpoints gradually. In our case we set this rate to a predefined default value, and let users adjust it. The difference in our approach is that we are not changing the virtual eye separation, but the image separation. Since we do not have any information about the visual system of the observer and the display hardware, the rate of change that is acceptable and comfortable will depend on the size of the images and the viewing configuration. Instead of directly applying the translation vector described earlier, we perform this change over a period of time using linear interpolation, which provides a smooth unnoticeable adjustment of the overall position of the scene in depth.

8.3 Stereoscopic Cursors

Commonly used cursors in most computer applications do not provide a perceptually sound mechanism for interaction with stereoscopic image pairs. When stereo pairs are overlaid with a standard monoscopic cursor, which is rendered at the same position in both views, then the cursor always appears to be at the plane of zero parallax. This is particularly inappropriate when the cursor is moved over opaque

[1] This is important when rendering with OpenGL's stereo buffers in a standard widget's window. Most window managers will only be able to supply the user's pointer coordinates in the coordinate system of the widget and not in the image planes' displayed within it. Normally one should remap these coordinates to identify the pixel location the user has selected.

scene objects that have negative parallax (i.e. are perceptually between the viewer and the display), because the visual system is signaled rivalrous stimuli at the location of the cursor. In 3D systems where the stereoscopic projective geometry is known, a stereoscopic cursor can be trivially rendered in both views with appropriate disparities and even research attempting to identify the shape of effective stereoscopic cursors has been presented by Barham and McAllister [5].

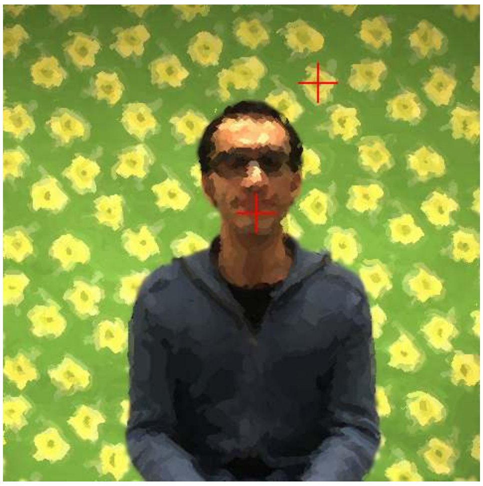
Nevertheless, in image-based software, e.g. stereoscopic image viewers, an appropriate stereoscopic cursor cannot be modeled directly. In addition, the goal is not to provide active manipulation of the stereoscopic content, but only the visual appearance of the scene. One way to provide stereoscopic cursors in image-based systems, such as ours, is to utilize dense disparity maps. In the following, we describe a simple stereoscopic cursor equivalent to the monoscopic cursor of standard graphical desktop applications and then we show how more advanced interactive tools, such as an image-based magnifying glass, can be designed.

8.3.1 Simple Stereoscopic Cursor

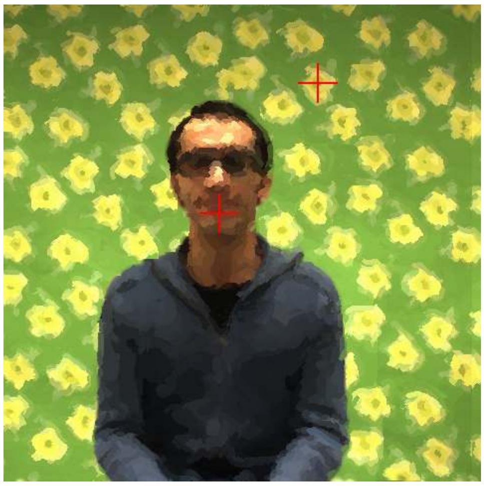
The simplest form of a stereoscopic cursor in our system is a target-like indicator of position, similar to the ones commonly used in photogrammetry. We want to model the perceptual position of the cursor to always be on the surface that is pointed at, therefore the pointer must be rendered at different locations in image space so that it can be perceived to float in space. We generate a cursor that is a cross made out of two orthogonal lines. In the reference view, the cursor is directly rendered with its center at the coordinates of the monoscopic cursor. The cursor in the coordinate space of the second view is generated by rendering the cursor at the same coordinates as in the reference view and applying a horizontal offset that is equal to the disparity value in the reference view converted to an image space displacement. Figure 8.2 shows a painting with two cursors rendered with appropriate disparities for two different points in space.

8.3.2 Stereoscopic Magnifying Glass

Magnification is a useful transform that allows a user to zoom into an image area and observe the finer details present. In monoscopic images this can be done in a number of ways. A simple approach is to select the region to be magnified and scale it by applying a linear or bilinear image interpolation. In an image-based stereoscopic context, however, this can only be done by scaling respective image regions from both images of the stereo pair. Scaling of respective regions alone is



(a)



(b)

FIGURE 8.2 *Figures (a) and (b) show the left and right components of a stereoscopic painting with two simple stereoscopic cursors rendered simultaneously (one on the person's face and the other in the background).*

not sufficient either for perceptually correct magnification. The magnified regions must be rendered with an additional disparity applied so that frame cancellation effects between the magnifier and the surrounding scene are eliminated.

To model an appropriate stereoscopic magnifying glass that can be used directly in a stereoscopic environment, we first define a shape (e.g. a rectangle, circle, etc.), which will act as the metaphor for the magnifying glass. The shape is centered around the image coordinates of the user's pointer in the left view. Just like the simple stereoscopic cursor described in the previous section, we retrieve the disparity value of the point and generate the coordinates of the magnifying glass in the second view. The shape is then texture mapped for each view by a magnified texture region of the respective original left and right textures.

For each of the vertices making up the shape of the magnifying glass, we generate texture coordinates that are the original vertex coordinates scaled by a zoom factor $z_f \in (0, 1]$. A zoom factor $z_f = 1$ produces no magnification, while a factor close to zero produces the maximum possible magnification. The area to be magnified in the original view is exactly defined by the shape of the magnifying glass, therefore a second user-defined parameter z_s can be used to change the size of the region to be magnified.

The disparity at the center of the magnified region in the reference view cannot be directly used to model the magnifier in the second view, because that would inadequately allow the magnifying glass to perceptually slice objects that are not planar. This would be the case if we used the same approach as with the simple stereoscopic cursor, since the whole planar shape of the magnifying glass would be sufficiently displaced in the second view to ensure that the magnifier is perceptually in front of the center, but would not account for points around the center that have higher disparities than the center. There are various ways to remedy this shortcoming by modifying the disparity of the magnifier's planar surfaces. For example, it would be sufficient to find the maximum disparity of the region to be magnified and dynamically adjust the disparity of the magnification planes. This would have the effect of the magnifying glass to shift perceptually at different distances without producing any conflicting cues between the magnification planes and the scene. However, we found that, when moving the magnifier, rapid changes in disparity caused it to abruptly shift between depth planes in order to remain always in front of them. A perceptually more stable alternative was to calculate the maximum disparity of the whole scene and apply it to the magnification planes at all times, thus bringing the magnifier at a distance from the viewer closer than any other feature in the scene. This is illustrated in Figure 8.3. If the disparities of the image planes viewed in the

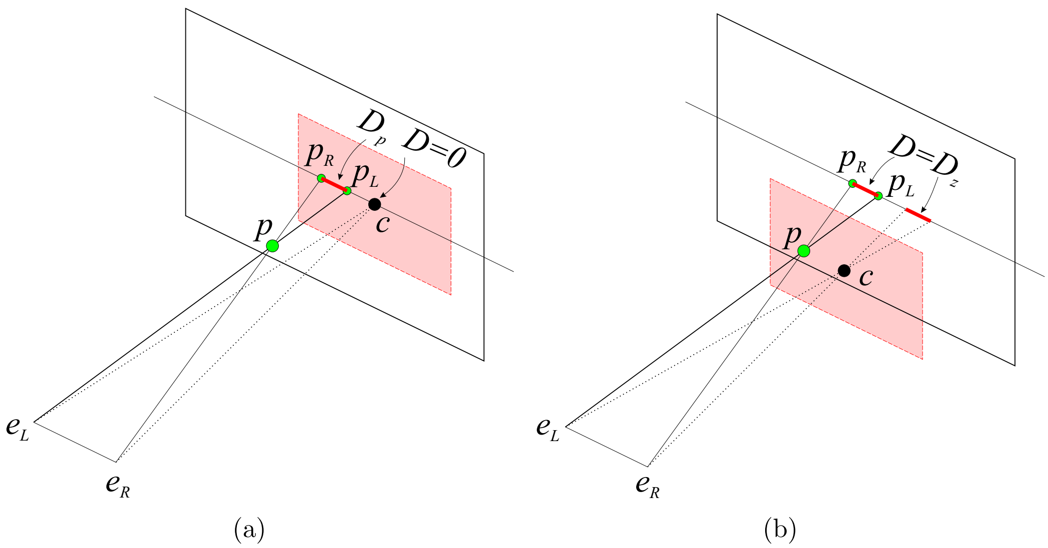
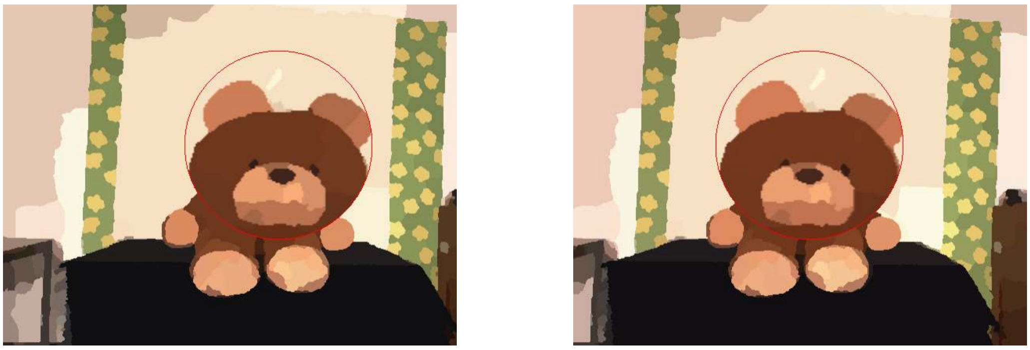


FIGURE 8.3 *A rectangular stereoscopic magnifying glass is shown with its center at the 3D point c. If zero disparity is applied, the magnifying glass is rendered at the plane of zero parallax, as shown in Figure (a). If we apply the maximum scene disparity, in this case at point p, to the center of the magnifier, as shown in Figure (b), c is perceptually shifted in 3D space, and all scene points will be perceived to be behind the magnifying glass.*

stereoscopic system are manipulated via the algorithms described earlier for horizontal image translation, the whole stereoscopic scene will perceptually shift from its original position. This may introduce an undesired conflict between the perceived depth at which the magnifier appears and the scene, therefore the respective horizontal image translation must be applied to the magnification planes, too.

In Figure 8.4, an example stereoscopic cartoon is magnified with a circular lens. The magnification techniques described here have very small computational payload and can be added to any real-time, image-based or not, stereoscopic system where a dense disparity map is available.



(a) (b)

FIGURE 8.4 *Figures (a) and (b) show the left and right components of a cartoon rendering with a circular magnification region.*

8.4 Observing the Anatomy of Stereo Artworks

The compelling feature of stereo artworks to encapsulate depth information motivates new interactive methods. It is not uncommon for observers of pictorial artworks to attempt to reverse engineer and "see" behind the finished work, even by using their imagination. Observers tend to do this in order to either understand the understructure of the work or visualize the development process. Having the ability to see a piece of art at any stage of its creation is particularly beneficial for art education and instruction.

In monoscopic works the process of the artwork's evolution can be captured and played back. The important aspect is the temporal order in which the marks making up the final work are placed by the artist. Computer-generated content is fairly easy to record and playback, and selected commercial applications for photo editing and painting (e.g. Corel Painter) provide this functionality already. Each and every step the artist takes when using a computer system, from concept sketching to finish, can easily be stored in digital form and later be reused. Common ways to present the evolution of monoscopic computer-generated artwork is to playback an animation of the creation process over time.

However, in stereoscopic works the temporal aspect of the artwork is not the only interesting hidden characteristic. Spatial structure beneath the surface of the artwork is significant in understanding how marks can be placed in the two stereoscopic components in order to produce an effective stereo work. Artists tend to work in the two stereo components in sequence; that is, to work on a particular area of the piece in the one component and then place similar marks on the second. The artist will then view the artwork in stereo to ensure that it provides an appropriate depth sensation and will continue this three-step iterative process to completion. It would be very tedious and mostly impractical to record the process of a stereo artist and play it back like in the case of monoscopic artwork. There would be need to switch between the monoscopic and stereoscopic modes that artists themselves use in the creation process, while they are working on the two components. Therefore the work will exhibit binocular rivalry throughout this process, except the individual snapshots that can be taken when the artwork is being checked for consistency (i.e. there are in both the left and right components equivalent marks). Note also that marks placed by the artist between the left and right stereo components rarely have a one-to-one mapping, down to the level of e.g. individual paint strokes. This is notoriously difficult to achieve by hand, and artists will ensure the final appearance will be stereoscopically consistent and not the intermediate states. This one-to-one consistency can be guaranteed by special stereoscopic devices built for the sole purpose of stereoscopic drawing and painting, such as Tamari's 3DD [115].

Our interest here is not to show the observer how the two components are made asynchronously, but to enable him to see through the artist's eyes at certain intervals over the spatial evolution of the work. We assume that the workflow of the artist involves a stereo pair of photographs that is used as a reference to create the artwork. The artist will first create a stereoscopic concept sketch and then progressively will use brushes, from large to small, in order to apply color.

To provide an intuitive user interface for viewing these stages and exploring the evolution of the painting over the z-dimension, we provide an orthographic projection of the whole stereo painting's structure to the viewer. At the farthest point from the viewer, the stereo photographic components, which were the input to our system, are placed so that their planes are perpendicular to the viewing direction. In front of these images a concept stereo sketch generated by our system is positioned. Since an orthographic projection is used to construct the viewing volume within which the observer is looking at the artwork, features will appear to have a constant size and will be perceived at the same depth (monocularly), regardless of how close to the viewpoint they are rendered. Incrementally, from back to front and coarse to fine, each paint layer that was calculated by the stroke-based painting algorithm is placed within the volume, as shown in Figure 8.5. The volume will then be sliced using a clipping plane in order to allow the viewer to see behind the finer strokes that occlude rougher strokes which are positioned further at the back.

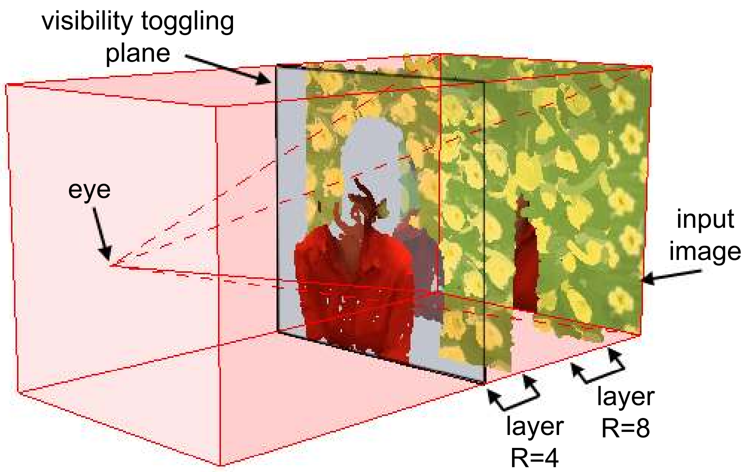


FIGURE 8.5 *A third-person view of the left component of a stereo painting with three layers. The user looks from the eye position. A consistent right view is calculated for the other eye.*

The viewing volume used to render the stereo artwork within is of $W \times H \times D$ dimensions and the eyes are at the plane where $z = 0$. The $W \times H$ dimensions of the frustum correspond to the size of the stereoscopic images used throughout the algorithmic processing. Recall that each stroke of an individual layer has an associated depth value d_S that is guaranteed to be within a range of $[0, 255]$, with 255 being closer to the viewpoint. However, strokes usually fall within a smaller range. We scale this subrange linearly so that depth values of strokes occupy the whole $[0, 255]$ range. This helps to increase the distance between strokes, because many scenes have a limited amount of depth and therefore strokes at different depths are usually densely distributed inside a smaller range of depth values. The motivation for this scaling is to increase the z-resolution of the paintings and allow the clipping plane to travel more distance between the strokes of an individual layer, providing easier control of the clipping plane to the end-user.

The overall depth D of the volume is calculated according to the amount of layers that are to be displayed within it, and an additional offset value for spacing the layers can also be applied. If there are N layers then $D = N(256 + offset)$. This ensures that the viewing frustum is sufficiently sized to accommodate all layers. If the roughest layer is considered to have an index $n = 0$ and for any refining layers n is incremented, then the overall z-position of each stroke S_Z of each layer can be trivially calculated as $S_Z = (256 + offset)(N - n) - d_S$. If we have not spaced apart the refining layers, then their differently sized strokes would be at the same distance from the viewer. Therefore, it would not be possible to use 3D clipping to toggle the visibility of individual strokes and, hence, slicing would not be intuitive.

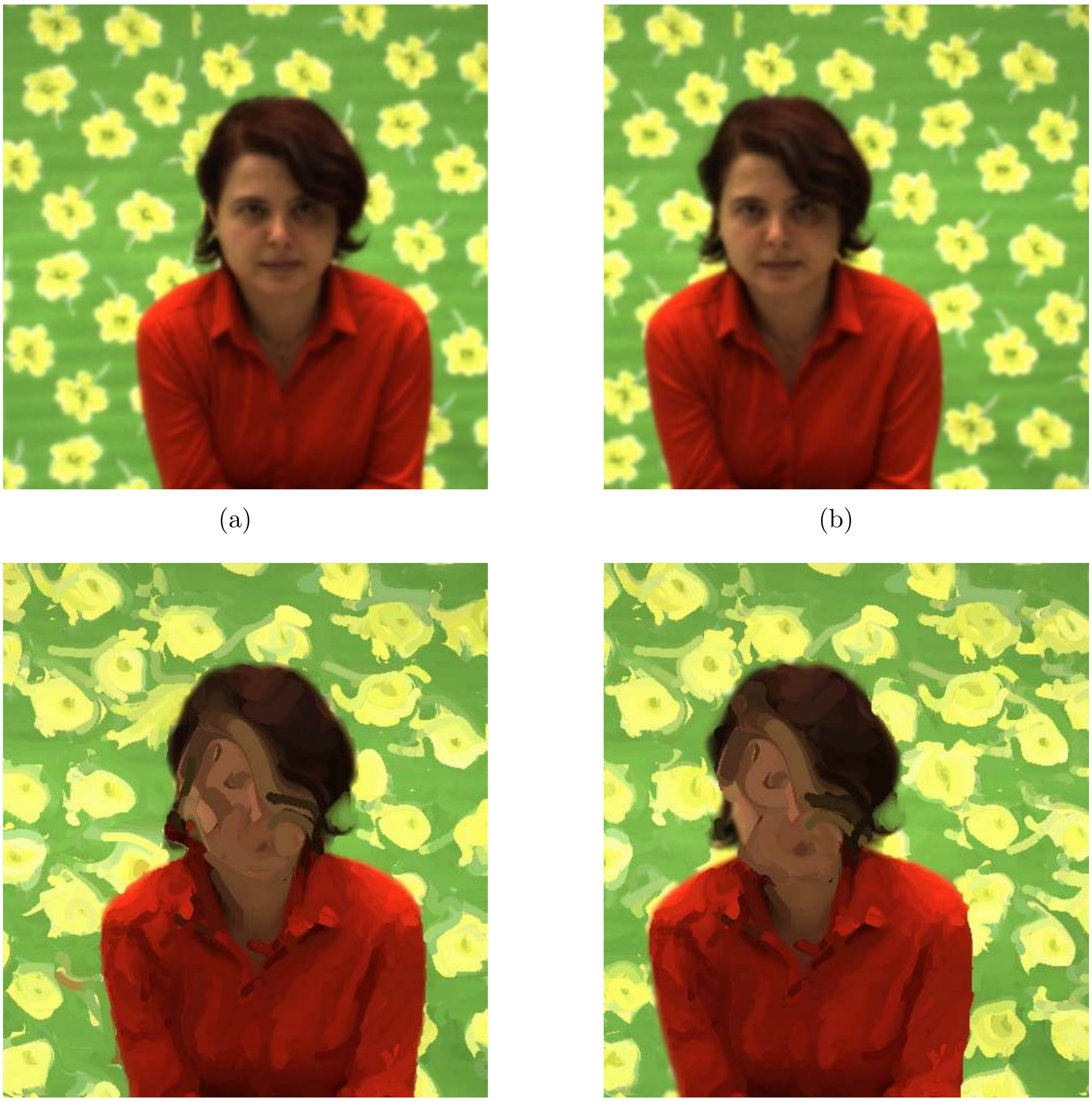
For instance consider the stereo image pair shown in Figures 8.6(a) and (b). When painted using three painting layers ($N = 3$), the stereo components are arranged as shown in Figure 8.5. The clipping plane provided to the user can be interactively shifted along the z-axis. Strokes that are between the viewpoint and the clipping plane are hidden, allowing the rougher layers to be seen. A slice through the painting can be seen in Figures 8.6(c) and 8.6(d). Clipping is equivalently performed in both the left and right stereo components and, since at every depth plane the visibility of the stereo primitives is consistently toggled, a stereo impression of the understructure can be perceived.

8.5 Discussion

The set of interactive methods described in this chapter aim to enrich the user's experience when viewing the stereoscopic content generated by our algorithms.

The implemented system is capable of self-adjusting some of its parameters according to predefined goals, such as preventing frame cancellation, but it cannot provide personalized stereoscopic viewing conditions without user interaction. Therefore simple interactive tools for manipulation and inspection of scene depth, as described in Section 8.2, can be an effective way to enable the end user to alter the stereoscopic content as desired. This level of interactivity is particularly useful in our image-based stereoscopic NPR system, since the system itself is agnostic of the potential end user's position relative to the viewing display. Thus, for example, it cannot predict the amount of horizontal image translation that would be more appealing for a given user. In addition, the stereoscopic cursor and the stereoscopic magnifying glass are means of inspecting the generated renditions, while the paint slicing tool demonstrates one of many possible mechanisms to allow a user to go beyond the traditional passive stereoscopic viewing of stereo artwork.

In essence, the collection of these tools allows the user to explore the stereoscopic space occupied by the stereo artwork within the stereoscopic space itself. By combining interaction techniques of both modes, i.e. manipulation and inspection, the artwork can be decomposed or explored by the spectator, while simultaneously maintaining an eye-strain-free stereo display, which further enhances the viewing experience.



(a) (b) (c) (d)

Figure 8.6 *Figures (a) and (b) show the input left and right stereo images, while Figures (c) and (d) show the left and right components of a sliced stereoscopic painting at a user defined section, as this is visible from the user's point of view.*

Chapter 9

Conclusions

9.1 Summary

In this dissertation we have combined computer graphics and computer vision techniques to propose a set of algorithms that can be used to transform stereoscopic images into stereoscopic pictures resembling artwork, including stereoscopic drawings, cartoons and paintings.

We start with a thorough inquiry into the area of stereoscopic fine arts (Chapter 2) that collects vital information for understanding the techniques used by traditional artists. Several problems and drawbacks surrounding the creation and viewing of stereoscopic artwork by hand have been identified. The ability of the medium to engage the observer into a world of spatial aesthetics and its profound advantage of effectively communicating depth information over other traditional visual media have been exposed and discussed.

In Chapter 3, we review relevant work in computer science, which is later combined with the knowledge drawn from our research in stereoscopy and fine arts. The outcome of this combination is a framework (Chapter 4) that captures a number of issues (e.g. feature correspondence, randomness, etc.), which arise within the context of applying stereoscopically Non-Photorealistic Rendering algorithms.

In the subsequent chapters we have shown that image-based stereoscopic rendering can be blended with NPR techniques to tackle the difficult problem of creating non-conventional stereoscopic imagery. We first presented a stereoscopic drawing algorithm (Chapter 5) that provides a basis for generating preliminary drawings. The stereoscopic lines generated by this algorithm describe rapid depth changes that provide the observer with silhouette cues, which particularly hint and assist the visual system to separate depth layers in a scene. We have demonstrated three main utilities of these stereoscopic drawings: (a) they can be used independently in any application requiring stereoscopic outlines that describe depth changes, (b) they can form the basis for more elaborate artworks, and (c) they can be utilized as a clipping mechanism together with other stereoscopic NPR algorithms to prevent depth discontinuity overruns.

The stereoscopic stylization algorithm of Chapter 6 demonstrates how purely computer vision techniques (e.g. image segmentation) can be used to preserve consistency across a synthesized stereo pair of pictures, while simultaneously stylizing colors. The designed algorithm may be used to assist the production of stereoscopic cartoons from real footage.

In Chapter 7, the techniques proposed to tackle stereoscopic painting show how existing NPR algorithms can be adapted to stereoscopy. Stereoscopic paintings can be very challenging to generate interactively, thus we propose simulating the painting process by taking into consideration the additional information provided by the use of stereoscopic images as an input. In particular, stroke-based rendering is adapted to account for depth discontinuities, to ensure consistent painting of the two views, as well as consistent generation of texture in occluded regions.

The proposed techniques generate output that can be presented as flat 2D images, or it can be spread over the z-dimension to enable interactive stereoscopic tools to be used (Chapter 8). As a proof of this concept, we have demonstrated how a simple stereoscopic cursor can be trivially modeled using disparities together with a more advanced stereoscopic magnifying glass that can be utilized to explore finer details of the artwork in stereo. In addition, we have shown how procedurally generated geometry, as in the case of the stereoscopic paintings, can be laid out in depth. The understructure of these paintings may be uncovered and visualized using a slicing mechanism, which enables viewers to see more than just the final artwork.

Disparity maps have played a pivotal role in this work. On the one hand, the stereoscopic correspondences encoded in them enabled us to preserve consistency across the generated stereoscopic views. On the other hand, they have been utilized to identify occlusions between the two views, which were then used to synthesize seamless and consistent texture between occluded and non-occluded regions of the same stereoscopic view.

9.2 Future Work

The work proposed here crosses the boundaries of computer graphics and vision and reaches out into fine arts within the context of image-based stereoscopy. Several aspects of the algorithms described require further experimentation and validation. Following is a list of topics that may be worth pursuing in the future.

- *Temporal stereoscopic Non-Photorealistic Rendering.*
  While stereoscopic video processing with computer vision algorithms is a particularly difficult problem to solve and the computation times can be significant, it would be possible to generate artwork that is not only spatially coherent, as we have shown in this work, but extended to also be temporally coherent. This may require the generation of temporal correspondence maps and the use of frame-to-frame coherent NPR algorithms. This would lead to useful applications mainly in entertainment (e.g. television, cinema), where stylized videos and cartoons may reach a large audience.

- *Interactive stereoscopic Non-Photorealistic Rendering.*
  Within the context of image-based rendering, interactive systems can be built that are targeted specifically to the fine artist. Currently, existing photo editing, painting and drawing applications allow artists to use a number of simulated natural media, brushes and working surfaces to develop digital artwork using photographs. Equivalent stereoscopic tools and software applications could be developed to fill in this vacuum. Computer vision algorithms can be employed to establish correspondences between input stereo photographs, which could be successively exploited by an automated system that lets the user draw or paint on the reference view, while the system as a deus ex machina generates the second view.

- *Exploring stereoscopic aesthetics further.*
  We have shown in this dissertation that certain interactive tools enable users to manipulate the stereoscopic space and affect the quality of the stereoscopic experience. More tools and interactive techniques could be built not only to explore preset stereoscopic content, but also to modify it. As stereoscopic aesthetics are not a deeply understood area and perceptual phenomena in single view artwork do not map directly into the stereoscopic domain, and vice versa, algorithms could be built to allow artists to manipulate stereoscopic space without the use of 3D modeling software. As an example, a system could allow artists to do playful use of disparities to achieve space inversion and color

mixing effects in a predictable way, similar to how affine transformations are applied to arrange elements of 2D visual artwork and how color mixers are used to apply colors.

- *NPR novel views.*
  Image-based rendering techniques are becoming more and more feasible in commodity hardware, and the widespread use of digital cameras suggests that NPR may have a significant impact in teleoperation and telecommunications. NPR may provide a better alternative to rendering photorealistic images in these domains, since such applications may require additional context-specific annotations to accompany the photorealistic images in order to make them more legible. Novel view generation of perceptually enhanced footage may lift the requirement of full 3D reconstructions and decrease computation.

- *Stereoscopic Illustration.*
  Stereoscopic illustration is widely adopted for communication of technical content because of its ability to communicate depth. Therefore, it can better expose the three-dimensional extents in a scene. Medical, industrial and educational sectors can significantly benefit from illustrative techniques that require only stereoscopic images as an input without the availability of 3D models. Even though the stereoscopic stylization technique we have proposed can be used for this purpose, illustrations usually require the modeling of transparencies and multilayer decomposable content that have not been tackled in this work.

Appendix A

Algorithm for Stereoscopic Painterly Rendering

The stereo painting algorithm used in this work is a variant of Hertzmann's [47] single-image painting algorithm based on the use of curved brush strokes of multiple sizes. For completeness, we briefly describe the original algorithm together with the modifications required by our image-based stereoscopic framework. Readers are encouraged to consult the original publication for a thorough discussion of all properties of the painting algorithm.

A.1 Stereoscopic Painting Algorithm

A list of brush stroke sizes of radii $R_i \dots R_n$ is used to paint progressively a series of layers, from coarse to fine. Each layer is created by filtering the original image I_{source} (either I_L or I_R) with a median filter, to obtain a reference image I_{ref}. The median filtered image is computed by convolving I_{source} with a pixel-centered kernel of size $K \times K$, where $K = 2 \cdot f_\sigma R_i + 1$, with f_σ as a blurring factor. The median filter's response gives rise to intensity edges that are helpful in distinguishing objects in stereo viewing.

A jittered grid is used to place strokes as described in the original algorithm. The jittered grid is an equally spaced grid with cell size $f_g R_i$, where f_g is a grid scaling factor. At a neighborhood $M \in I_{ref}$ of size $(f_g R_i) \times (f_g R_i)$ around each grid point, we find the pixel in M that has the maximum Euclidean distance, in RGB color space, from its corresponding pixel in the image I_{canvas}, which is the image we progressively paint on. If this distance is above a threshold T, we plan a stroke by defining the first control point (x_0, y_0) of the spline brush stroke at that location.

To order the strokes that paint the respective canvas I_{canvas} for I_{source}, we generate a random list of numbers that is equal to the maximum value of the depth map's histogram. The maximum value of this histogram can be thought of as the maximum amount of brush strokes that may be painted on the canvas at a particular depth value. From the largest to the smallest depth value, we order and render all strokes at each depth value by using the random list, effectively avoiding regularity that may occur in areas where successive strokes may have the same depth (i.e. a surface perpendicular to the viewing direction). For views where a disparity map is unavailable a zero valued disparity map is assumed.

To create the stereo painting, we first use the process described above on I_L to generate the left painting. We apply paint on all pixels of the left image. We then process I_R, but we now take into consideration the pixel locations of the right view that could not be seen from the left, which are encoded within an occlusion mask I_{occ}. We allow strokes to be initiated only from the image locations of occluded pixels. By clearing the occlusion mask, the complete view is considered for stroke placement. The occlusion map remains constant between refining layers and the strokes are allowed to expand beyond the borders of the occluded regions. Once the painting of occluded areas is completed, the disparity map is used to transform the left painting atop of the current painting of I_R.

A.2 Stroke Creation

The spline stroke planning procedure places control points (x_i, y_i) normal to the direction of the gradient of the Sobel-filtered luminance of I_{ref}, at a distance of R_i. The color of the brush stroke is set to the color of I_{ref} at the location of the first control point (x_0, y_0). Note that a stroke can only be initiated from a location at which an occluded pixel is present, when painting the right image. We continue to place control points until one of the following criteria is met:

(a) a predefined maximum number of control points has been reached,

(b) the difference between the color of I_{ref} at (x_{i-1}, y_{i-1}) and the constant brush stroke color is larger than the difference between the color of I_{ref} and the color of I_{canvas} at (x_{i-1}, y_{i-1}),

(c) the magnitude of the gradient of the Sobel-filtered luminance of I_{ref} becomes zero,

(d) any pixel P within a distance from (x_i, y_i) smaller than R_i has an absolute difference of depth value from the depth value at (x_i, y_i) which is greater than a predefined depth threshold T_{depth}.

Termination criteria (a) through (c) are part of the original algorithm, we introduced criterion (d) to handle *paint spilling* as explained next.

As we discussed in Section 4.1, *paint spilling* over neighboring surfaces at different depths may be uncomfortable to see in a stereo painting. Termination criterion (d) of the stroke creation algorithm prevents *paint spilling.* The problem arises because, as the spline stroke is being planned, control points may be located inadequately close to a depth discontinuity, which will cause paint to spill beyond the object's boundaries. This happens because the stroke has a width of R_i and when painted, it will extend further from where the actual spline has been planned. Calculating the difference between the depth value at the current control point location and each pixel's depth value within a window of size $(2 \cdot R_i + 1) \times (2 \cdot R_i + 1)$ around it, ensures that no depth discontinuities larger than T_{depth} are in proximity and the control point can be added to the stroke. In addition, the pixels tested for depth difference include all the possible locations for the next candidate control point, which should be placed at a distance R_i.

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Figures

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Curriculum vitae

Efstathios Stavrakis was born in 1979 in the island of Lesvos, Greece. He received a Bachelor of Arts in Creative Visualisation at the University of Teesside in 2000. The next year, at the same university, he was awarded the Master of Science in Computer-Aided Graphical Technology Applications (CAGTA) with distinction. In 2002 he moved to Austria to work toward a PhD degree at the Interactive Media Systems group at the Institute for Software Technology and Interactive Systems of the Vienna University of Technology. He also joined the Computer Graphics group of the Institute of Computer Graphics and Algorithms in 2007. His research efforts have been focused on techniques at the intersection of computer graphics and vision, in particular on non-photorealistic and stereoscopic rendering.