Chapter 1

Introduction

1.1. Motivation

The work described in this thesis is motivated by the desire for realistic texture synthesis in augmented and virtual reality applications, which play important roles in film and computer game industries. For example, as a commonly used technique to enhance realism, texture mapping normally requires an input texture of an adequate size. If the size is inadequate, texture synthesis techniques can be employed to generate a large texture using the small sample. Although repeatedly tiling the sample can produce a large image, notable seams and discontinuities will appear in the result image for many textures. The result therefore can not be perceived as a homogeneous texture. Figure 1.1.1 shows a simple example of the tiling effects and seams produced by repeating a sample image on the surface of a cubic box. Thus, the main purpose of texture synthesis is to synthesise a large texture image that is perceptually identical to the small sample for the human vision system. Recent texture synthesis techniques have been able to efficiently synthesise a wide range of real-world textures. Figure 1.1.2 shows an example; the result image is synthesised using the algorithm proposed in [Efros2001].

However, real-world textures are seldom “flat” and normally comprise rough surface geometry and various reflectance properties, which can produce dramatic effects on the appearance of the sample surfaces under varied illumination and viewing conditions. Figure 1.1.3 shows two example images of a 3D surface

texture—a piece of wallpaper illuminated from two directions. The difference is obvious. This presents challenges in both computer vision and computer graphics. It is therefore important to capture the characteristics of 3D surface textures so that new images illuminated from different directions can be produced. Photometric Stereo (PS) is one of the commonly used methods and can generate surface gradient and albedo maps from three images of a non-shadowed Lambertian surface [Woodham1981]. The surface gradient maps can be further integrated to produce a surface height map (surface profile). With the albedo and height or gradient maps, new images of a Lambertian surface under arbitrary illuminant directions can be generated. Figure 1.1.4 shows the surface height and albedo maps of a wallpaper patch.

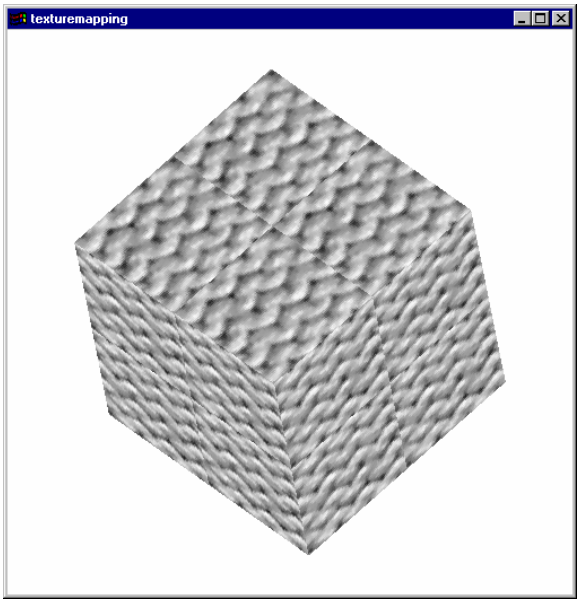

Figure 1.1.1 The tiling effects produced by mapping a texture image of an inadequate size using standard OpenGL functions. On each surface of the cubic box, the texture is repeated four times in order to cover the whole surface. Seams are obvious.

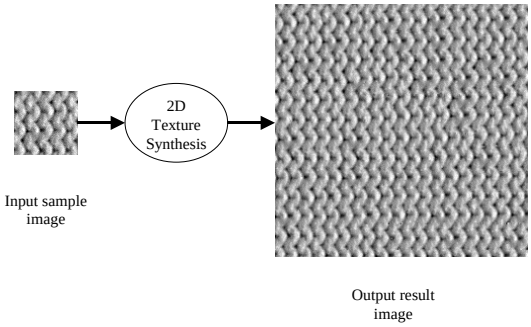

Figure 1.1.2 Texture synthesis using the algorithm proposed in [Efros2001].

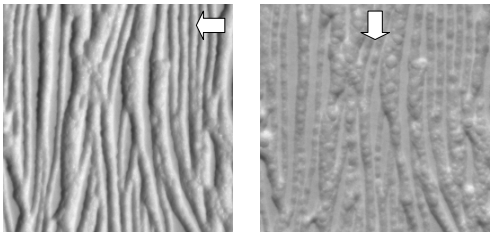

Figure 1.1.3 Two images of a 3D surface texture illuminated from different directions. The block arrows show the illuminant directions.

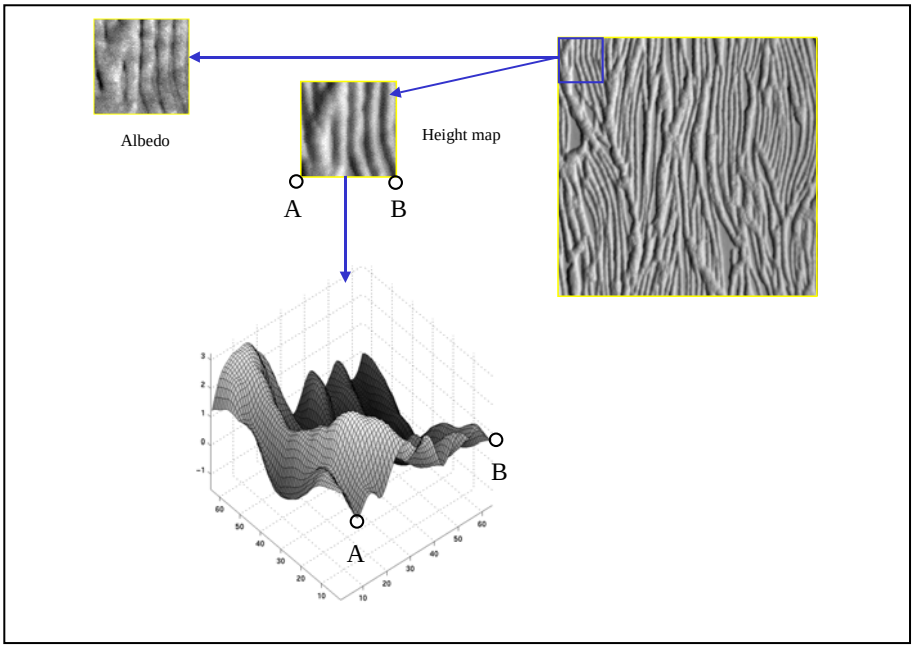

Figure 1.1.4 A 3D surface texture can be described using the surface height and albedo maps.

In recent years, texture synthesis has been extensively investigated by both computer vision and computer graphics communities. However, the input and output are normally 2D intensity images. If the subjects are 3D surface textures (such as brick, woven or knitted textiles, embossed wallpapers etc.), these 2D synthesis techniques cannot provide the information required for rendering under other than the original illumination and viewpoint conditions. This presents difficulties in realistic rendering in many augmented and virtual reality applications and has inspired the work described in this thesis—we wish to develop reliable and inexpensive methods for the synthesis of 3D surface textures.

In the research field of 3D surface texture synthesis, few publications are available [Zalesny2000, Zalesny2001, Liu2001, Shum2002 and Leung2001]. The aim of this thesis is therefore to develop inexpensive approaches for synthesising and relighting 3D surface textures. The synthesised results should be compatible with the input requirement of computer graphics packages and modern graphics systems so that real-time rendering can be achieved.

1.2. Scope of the research

In order to explicitly describe the work in this thesis and avoid confusions, we first summarise and list the definitions of commonly used terms. We then introduce the scope of our research.

1.2.1. Definitions of terms

Table 1.2.1 shows the definitions of terms used in this thesis.

Terms	Definition	First introduced
3D surface texture	Topological texture comprising 3D variation of surface geometry and reflectance	Section 1.1
2D texture	An intensity image of the sample texture.	Section 1.2
2D texture synthesis	Synthesising a large image using a small intensity image of the sample texture.	Section 1.2

	This is identical to the term *texture synthesis.*	
3D surface texture synthesis	Synthesising new texture images under different viewing and lighting conditions. The input sample data for 3D surface texture synthesis can be a set of intensity images or surface representations of the sample texture.	Section 1.1
Texture images	Images produced by illuminating 3D surface textures	Chapter 2
Input sample images	The intensity images used for 2D or 3D surface texture synthesis	Section 1.1
Output result images	The synthesised images output by 2D or 3D surface texture synthesis algorithms	Section 1.1
Photometric image set	A set of images captured under varied illumination directions using a fixed camera. Also called *photometric images*	Section 3.3
Surface representations	The set of representations extracted from a set of photometric images. They can be used to produce new images under different illumination directions. Also called surface relighting representations or representation maps.	Section 1.2
Relit images	The images produced by relighting surface representations	Section 1.3

Table 1.2.1 Definition of terms

1.2.2. Scope of the research

The work described in this thesis involves the following research:

(i) selecting and investigating suitable surface representations for the synthesis of 3D surface textures under arbitrary illumination directions,

(ii) selecting and investigating suitable 2D texture synthesis algorithms that can be efficiently extended to synthesise surface representations in multi-dimensional space, and

(iii) developing and assessing 3D texture synthesis approaches.

Figure 1.2.1 shows the scope of our work described in this thesis.

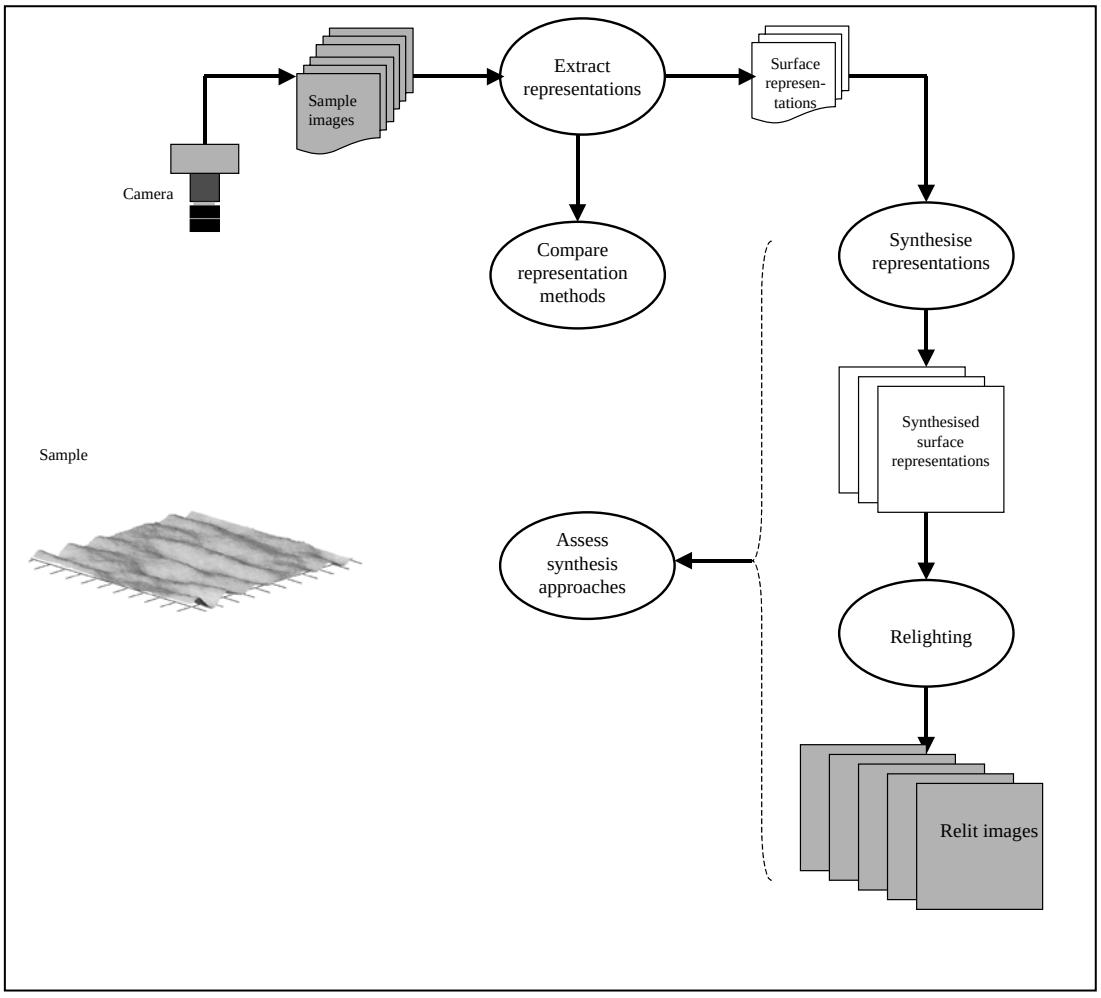

Figure 1.2.1 The scope of research in this thesis

This thesis concentrates on synthesising 3D surface textures with varied illumination directions. The illumination is assumed to be unidirectional. The viewpoint is assumed to be fixed and vertically above the surface textures, which are placed in a horizontal plane. Although using computer graphics programming techniques or software packages can achieve the effects produced by varying

viewpoints and illumination simultaneously, the description and research related to these topics are beyond the scope of this thesis. The synthesised 3D surface textures are compatible with computer graphics systems and can be effectively rendered using linear combinations in graphics hardware. However, this implementation will not be described in detail in this thesis. Readers can refer to [Robb2003] and [Burschka2003] for the latest developments on real-time graphics programming techniques using modern graphics hardware.

1.3. Thesis organisation

This thesis consists of seven chapters. Chapter 2 provides an overview of the research fields related to the thesis. Based on this survey, we present a framework for the synthesis of 3D surface textures in chapter 3. According to the framework, we then investigate and select suitable surface representations and 2D texture synthesis algorithms in chapter 4 and chapter 5. In chapter 6, we describe and compare five approaches for the synthesis of 3D surface textures. Chapter 7 summarises the work in this thesis and briefly discusses the use of synthesised results in computer graphics programming and software packages.

In chapter 2, we survey three research fields: (1) 3D surface texture synthesis, (2) 2D texture synthesis and (3) surface representation methods for relighting. Based on the survey, we conclude that there are only five publications available concerning 3D surface texture synthesis, while many techniques have been published in the other two research fields. Thus, we propose an overall framework for the synthesis of 3D surface textures in chapter 3. The framework essentially combines surface representation methods with 2D texture synthesis algorithms to synthesise 3D surface textures under arbitrary illuminant directions.

Based on the overall framework, chapter 4 reviews the available surface representations and selects five inexpensive methods for investigation. We propose a mathematical framework for the selected five methods and then describe each individual method. The performances of these methods are quantitatively assessed by comparing relit images with original real images under multiple illumination directions. We analyse the assessment results and in particular discuss the problem

associated with a heightmap-based representation, which is obtained by integrating surface gradient maps.

In chapter 5, we review the available 2D texture synthesis publications and select two methods based on [Wei2000] and [Efros2001] as the candidates of basic algorithms for 3D surface texture synthesis. We then investigate and compare the two methods in terms of the quality of synthesis results and computational complexity. The comparison shows that the algorithm based on [Efros2001] produces better performance. We therefore select it as our basic synthesis algorithm. The effects on output images produced by varying input parameters are also analysed.

In chapter 6, we describe five 3D surface texture synthesis approaches that combine the five surface representations with the basic synthesis algorithm. We then perform psychophysical experiments to qualitatively assess the performances of the five synthesis approaches, as no ground-truth data is available for a quantitative comparison.

Finally, we summarise and conclude our work described in this thesis in chapter 7. We also discuss the simple use of synthesised representations in graphics programming and software packages.

1.4. Original work

It is believed that this thesis contains the following original work:

1. An overall framework and five inexpensive approaches are proposed for the synthesis of 3D surface textures. In the literature, only five publications are available in this research field. This thesis, together with our previous publications, makes important contributions in the research field of 3D surface texture synthesis.
2. In chapter 4, a mathematical framework that summarises five surface representation methods is proposed. This framework exclusively reveals the relationships between the five surface representations using mathematical formulas.
3. In chapter 4, five surface representation methods are quantitatively compared. The comparison provides quantitative measurement for their performances in

representing 3D surface textures under different illumination directions. The problem of integrating surface gradient maps to generate surface height maps is also discussed. It is believed that it has not been investigated and reported before.

4. In chapter 6, an assessment method based on psychophysical experiments is proposed to qualitatively compare the five 3D surface texture synthesis approaches. It is believed that very little has been published on the systematic qualitative assessment of texture synthesis results.