CHAPTER 10

Summary and Conclusion

10.1. Summary

The objective of this thesis is the development of the classifiers that are capable of discriminating between surface textures on the basis of their visual appearance, yet which are robust to the changes of surface orientation.

Many texture classification schemes have been presented that are invariant to image rotation. All of these algorithms deal with the rotation of image texture. However, in this thesis it is argued that this is an insufficient model for many applications. Rotation of a rough surface is not equivalent to the rotation of the image. It follows that rotation invariant algorithms will not be robust to surface rotation and the conventional image rotation invariant algorithms may fail under certain conditions. An example phenomenon is illustrated in *Chapter 1*. This is the motivation for this thesis in which we develop a surface rotation invariant texture classification scheme.

Chapter 2 surveys texture feature measurements and rotation invariant texture classification. Before we discuss the texture features, some definitions of texture, surface relief and albedo are given. We note that most of rotation invariant feature methods are based on image rotation rather than physical surface rotation. Furthermore, there are few methods in which the effect of changing illumination conditions are taken into account.

The formation of the image from the surface is considered in *Chapter 3*. Firstly, a review of related work on reflection and illumination modelling is given. Afterwards, a simple Lambertian illumination model is selected, and it is proven to describe diffuse reflection well. Secondly, we present Kube and Pentland's model, a linear Lambertian model, which assumes fixed illumination and viewing geometry and expresses observed intensity as a linear function of surface partial derivatives. Furthermore, the formation of Kube and Pentland's model in the frequency domain enables the directional effect of illumination to be more easily understood, and its directional filter is also investigated. One of important conclusions is that image variance is not a surface rotation invariant feature for directional surfaces. In addition, the non-linear effects neglected by the Kube and Pentland's model are considered. Their effect on surface amplitude variance, frequency doubling and intensity clipping is investigated through the use of simulation. This confirms Kube and Pentland's s linear model must be used on the basis that surface height variance is low and that the slant angle does not approach *0* degrees. Finally, we briefly introduce four models of rough synthetic surfaces, which are used in this thesis for the purpose of simulation.

We demonstrate in *Chapters 1* and *3* that the rotation of a directional surface is not equivalent to the rotation of its image. We therefore classify the surface texture using the properties of the surfaces rather than those of images so that an intrinsic characteristic of a surface has to be recovered prior to the classification. Photometric stereo is presented in *Chapter 4*, which enables us to estimate surface orientation and surface albedo using several images of the same surface obtained under different illumination directions. It has no smoothness assumption, only requires additional lighting and can be easily implemented at a reasonable computational cost. Furthermore, the surface orientation captured by photometric stereo in *Chapter 4* is mapped and examined in the spatial gradient space domain by means of moment analysis in *Chapter 5*. However the estimation process on non-directional texture surfaces provided poor results, because a gradient space image is *n-fold* symmetric where there are multiple possible sets of principal axes. We will discuss how to remove directional artefacts in the frequency domain in *Chapter 6*.

Having recovered the surface orientation using photometric stereo, the second part of this thesis addresses the design of the classification scheme, which is robust to surface rotation.

Chapter 6 describes the first stage of the design of the classifiers. This Chapter begins by introducing photometric stereo in the frequency domain. Because the surface partial derivatives are not surface rotation invariant features, we combine them in the frequency domain. The resulting gradient spectrum function is therefore free of directional artefacts. Secondly, the results from using both synthetic and real textures are used to show one important property of gradient spectrum: a rotation of the surface produces a corresponding rotation of its gradient spectrum. Thirdly, since comparing the gradient spectra of a test texture with those of the training classes over a complete range of rotations is computationally prohibitive, we extract a *1D* feature space, the polar spectrum, from its *2D* gradient spectrum to retain the directionality information. The results also show that a rotated texture's polar spectrum is equivalent to a translation of its polar spectrum. In other words, the surface orientation can be estimated from the polar spectra. Finally the complete classification scheme is described in *Chapter 6*.

In *Chapter 7*, we present the experimental procedure and classification results for the scheme described in *Chapter 6*. Since currently existing and publicly available texture databases are not suitable for our task, we develop a photometric stereo texture database, which includes *4* synthetic textures and *30* real textures with various surface rotations and illumination conditions. The average classification accuracy of *100%* is obtained while using *4* synthetic textures, on the other hand, the accuracy of *76.30%* is achieved using *30* real textures. After fully investigating the misclassifications we introduce a new classification feature space: the radial spectrum; and a new feature generator: albedo spectra. The comparative classification results show that this provides more discriminative ability. Our new classification scheme achieves better results with a classification accuracy of *90.56%* for *30* real textures.

The problem of shadowing using three-image photometric stereo is considered in *Chapter 9*. We develop a four-image system to provide more accurate estimation of *3D* surface texture properties. Furthermore, one reason of misclassification is that we only compare *1D* spectra features (*polar* and *radial*). These *1D* spectra are integrals of the original *2D* spectra (*gradient* or *albedo*). Two textures with different *2D* spectra may well have the same *1D* spectra. Therefore a final verification step is included where the *2D* spectra are compared. This *2D* comparison is not costly because the rotation angles are already known from their *1D* polar spectra. Finally, we achieve the classification accuracy of *99.07%*.

While our results using real surface textures are even higher than those published for some image rotation invariant schemes [Cohen91] [Reed93] [Hayley96] [Port97] [Fountain98] [Zhang02a], they are good considering the difficulties involved with the rotation of real 3D surface textures and the large number of different texture classes presented. However, our algorithm is still not perfect at the classification accuracy of *99.07%*. Comparing to Varma and Zisserman's method [Varma02a] [Varma02b], which is achieved to a classification accuracy of *100%* by using our photometric texture database, we note that they use more images than ours as training set (*28* images per texture class). On the other hand, we only use *4* images per texture class. In addition, the surface orientation can be estimated at the same time of the classification, while Varma and Zisserman's method does not do it. The limitation of our algorithm is that we need controlled illumination conditions, and computational cost is heavy by considering the rotation of 2D spectrum.

10.2. Future Work

This work investigates a rotation invariant classification of *3D* surface texture using photometric stereo. Surface gradient and albedo information can be recovered by using registered photometric image set where the illumination directions are known. However in many cases of real world, the illumination directions of images for *3D* surface are unknown, therefore the position of illumination source has to be estimated or precision calibration of the illumination is required before applying registered photometric stereo. This will lead to investigation of non-calibrated photometric stereo.

In this thesis, we only change the tilt angle of illumination direction in order to achieve the different illumination conditions. While changing the slant angle of illumination direction can produce the same situation however, it will result in the effect of self or cast-shadowing introduced. It is worthwhile to investigation of how our classification algorithm is robust to illumination tilt and illumination slant angles.

One of the assumptions about *3D* surface textures in this thesis is that there is no inter-reflection. However, the inter-reflection has to be considered in real world. Nayar has raised this problem and investigated the possibility of shape recovery from inter-reflections [Nayar91b]. This matter should be investigated on photometric stereo, too.

10.3. Conclusion

This thesis has used theory, simulation and laboratory experiment, to investigate the rotation invariant texture classification for *3D* surface using photometric stereo.

We have presented a new surface rotation invariant texture classification scheme that uses photometric stereo. It combines polar and radial spectra of gradient and albedo data. We have shown that the image rotation is not equivalent to the rotation of rough surface. We have therefore presented theory and experimental results that show that our basic feature spaces of polar and radial spectra of gradient and albedo data are free of directional artefacts and that they may be used as discriminate features in surface rotation invariant classification.

Results using our texture database show that combining the gradient and albedo data improves the classification performance. The best classification rate of *99.07%* is achieved by using the combination of *1D* and *2D* features.

Some possible applications applying to our technique are detection of machined surface defects in industry, classification of satellite images in order to landmark the terrain, recovery topography and albedo of rough surface with fingerprint, recovery of imprints from clay tablets in archaeology and texture mapping on *3D* rough surface.