Chapter 7

SUMMARY OF RESULTS

This chapter summarises what has been achieved for each of the images used in the book. Sometimes an operation on an image was performed simply to illustrate an idea, but on other occasions progress was made towards the aims described in §1.1.3. The success in doing this varied, and we shall try to make a fair assessment of what has been accomplished. In some cases more complex techniques, beyond the scope of this book, would be called for, and we shall point towards relevant literature. In other cases, techniques have not been adequately developed at the time of writing: image analysis is an active area of research.

The layout of this chapter will be a series of summaries of the achievements for each of images listed in Table 1.2.

- **Algal cells**: The DIC microscope image of algal cells is shown in Fig 1.6(a). The aim was to count and measure the cells. The first stage was to apply a threshold to the image in order to segment the darker parts of the cells from the background (Fig 1.12(d); thresholding is discussed in §4.1.1). Then a morphological opening was used to separate pairs of touching cells and reduce the roughness of the cell boundaries (Fig 1.12(e); discussed in §5.2). Alternatively, the watershed algorithm (§4.3) could have been applied to the distance transform of the binary image (§5.2), as described by Serra (1982, pp 413-416).

  Size and shape statistics of cells were extracted from the segmented image. These included moment statistics (Table 6.1), perimeters, lengths and widths, and measurements of shape such as compactness and elongation (Table 6.2). Fig 6.8 is a display of the relative shapes of the dark parts of the cells. The statistics could be used to discriminate between different types of algae.

  The measurement is successful, although most of the statistics have been affected by the fact that the bright parts of the cells were lost after the thresholding. This problem could be overcome by calibration, or by an approach based on multiple thresholds and morphological operations. More sophisticated approaches could take account of the specific optics of DIC microscopy (Holmes and Levy, 1987 and 1988).

- **Cashmere fibres**: The microscope image of cashmere goat fibres is shown in Fig 1.6(d).

The image was obtained in order to measure the fibre diameters. This is made more difficult because the fibres appear differently according to their position relative to the focal plane. The image was used in Fig 3.1 to illustrate the different types of linear filter (smoothing, edge finding and unsharp masking). The amplitude and phase of the Fourier transform of the image are shown in Figs 3.5(c) and (d).

In §5.5, a sequence of greyscale morphological operations was used to determine the distribution of diameters. There is, however, scope for further refinement of this approach, and for taking account of bias in diameter estimates of fibres at different focal planes — see, for example, Glasbey, Hitchcock, Russel and Redden (1994).

- **DNA sequencing gel**: The autoradiograph is shown in Fig 1.9(c). This example of an electrophoretic gel is one-dimensional because gene fragments only migrate in one direction — down the separate tracks. In Fig 1.10 we showed the difference between the original photographic plate and the digitized image. The positions of the bands in each track are of interest. We did not attempt to automatically find the band positions, but used some techniques to make this easier for the human interpreter.

  In §3.2.3, we showed how it is possible to reverse blurring in an image, by deconvolution using the Wiener filter. This involved modelling the degradation process, in order to identify the optimal linear filter. In §3.4.2, we showed how Prewitt's edge filter could be used to find edge directions, the results of which are displayed in Fig 3.18 (colour plate). These orientations can be used to remove warping from an autoradiograph (Glasbey and Wright, 1994). In §5.4, the image was used to illustrate the measurement of texture based on the auto-crossproduct function, and in §5.5 it was shown how the top-hat transform could be used to subtract the trend in background brightness and so make the bands more distinct.

  For work on automatic detection of bands in DNA sequencing gels, see Griffin and Griffin (1993), Khurshid and Beck (1993) and Smith (1993). Analysis of one-dimensional gels in general is considered by Trubuil (1993).

- **Electrophoretograms**: Figs 1.9(a) and (b) show a pair of SDS-PAGE gel electrophoretograms. The aim was to recognise differences between the gels. In §2.5 it was shown how the gels may be aligned using registration techniques. Then the colour composite, shown in Fig 2.17 (colour plate), makes it easy to identify the differences in location of a few spots. Meyer and Beucher (1990) used greyscale morphological operations to identify spots. It is then possible to estimate protein volumes by summing the pixel values (§6.1.1).

  Many attempts to automatically analyse 2-D electrophoretic gels have been described. See for example Appel, Hochstrasser, Funk, Vargas, Pellegrini, Muller and Scherrer (1991), Conradsen and Pedersen (1992), Nokihara, Morita and Kuriki (1992) and Solomon and Harrington (1993).

- **Fish**: The fish image is shown in Fig 1.9(e). The aim was to extract information about the shape of the fish, which could then be used, in conjunction with images of many other fish, to discriminate between different species. There are many ways of quantifying shape. Strachan, Nesvadba and Allen (1990a) looked at statistics based on dividing the fish into a number of quadrilaterals and measuring their orientation and average grey

level. Glasbey, Horgan, Gibson and Hitchcock (1995) explored two statistical theories of shape, those of Procrustes methods (Goodall, 1991) and morphometrics (Bookstein, 1991).

In §2.3.2, the fish image was used to illustrate the way that pseudocolour makes greyscale comparisons easier than in a standard display. In §6.3 we showed how the fish outline could be described using a boundary chain code, once the fish has been distinguished from its background. The segmentation was achieved using a semi-automatic method which involved thresholding, and the use of a computer mouse to complete the boundary. An alternative approach, discussed in §1.2, is to make use of a second, back-illuminated image. Fig 6.11 shows the fish boundary approximated by varying numbers of Fourier descriptors. Since these summarise aspects of the shape of the outline, it should be possible to use a selection of the Fourier descriptors to construct a discrimination between species. For more recent work, involving the use of colour in discrimination, see Strachan (1993).

- **Fungal hyphae**: The digitized photograph of part of a fungal mycelium is shown in Fig 1.9(d). The image was obtained in order to further understand the spatial distribution of hyphae. The image was used to illustrate binary image display in §2.1 and zooming and reduction in §2.4.

  In §5.3, a thinning operation was used to obtain the skeleton. This reduced the hyphae to the thickness of a single pixel, which is convenient for estimating the total length of hyphae. In §5.4, the spatial arrangement of the hyphae was examined by calculating the auto-crossproduct function. This showed no obvious pattern, suggesting a uniform distribution of orientations. The total hyphal length was estimated in §6.1.2, with allowance made for effects due to lines being represented as lattice points rather than in continuous space. Further work on fungal morphology, and its relationship to soil structure, is described by Crawford, Ritz and Young (1993).

- **Landsat**: Thematic Mapper bands 1-5 and 7 from the Landsat satellite are shown in Fig 1.8(a)–(f) for a region on the east coast of Scotland. In combination they form a multispectral image. There are many uses for such images, ranging from cartography to environmental monitoring. A comprehensive reference is Colwell (1983).

  In §2.2.2, it was demonstrated how the greyscales of individual bands could be stretched to make features easier to recognise. In §2.3.3, a natural colour display was produced from bands 1, 2 and 3. This is shown in Fig 2.10 (colour plate). A standard use of satellite images is to classify ground cover. This can be done using the multivariate and contextual classification methods described in §4.1.2 and §4.1.3. Facilities to do this are available in most software designed for remotely sensed image handling. In §6.1.1, we showed how areas of a particular crop type (oil-seed rape) could be estimated after multivariate classification.

- **Magnetic resonance images**: MRI inversion recovery and proton density images are shown in Figs 1.7(a) and (b). Together, they constitute a bivariate multimodal image. The interest was in estimating the cross-sectional areas of different tissue types. In §6.1.1 we briefly discussed the thorough job done by Fowler *et al* (1990) in calibrating their experiment, to estimate volumes and water content.

Fig 2.11 (colour plate) is a colour display of the bivariate image, which reveals differences between tissue types more readily than does an examination of the two separate images. In §4.1.2, linear discriminant analysis was used to classify pixels into four tissue types: lung tissue, blood in the heart, muscle and subcutaneous fat. In addition to this, the images were used to illustrate the possibilities for unsupervised classification using k-means clustering.

Because MRI imaging is widely used, much work has been done on the automatic analysis of such images. See, for example, Colchester and Hawkes (1991) and Barrett and Gmitro (1993). Recent interest has centred on analysis of three-dimensional images and on multimodality — the synthesis of images produced by different technologies.

- **Muscle fibres**: Fig 1.6(b) is a stained section through a muscle, showing three fibre types. The aim was to count and measure the sizes of fibres of the different types.

  This image was first used, in §2.2.2, to illustrate histogram equalization. This made the variation in pixel values within each fibre easier to see (Fig 2.7(d)). The muscle fibres image was used extensively in chapter 4 to illustrate different approaches to segmentation, including thresholding (§4.1), edge-based methods (§4.2) and a region-based method using the watershed algorithm (§4.3). Fibre sizes in a segmented image can be measured using the methods described in chapter 6.

  It has proved difficult to achieve a fully automatic segmentation of this image, and work is still in progress (Glasbey and Maltin, 1994). The main difficulty is that some divisions between fibres are very faint. The human eye, in recognising fibres, is making use of the fact that the fibres seem to have a convex shape and a narrow range of sizes. It seems likely that any fully-automatic segmentation would also need to make use of this. More-complex segmentation methods are discussed at the end of chapter 4.

- **SAR**: A synthetic aperture radar image is shown in Fig 1.8(g). This image can be used in the same way as the Landsat data, for application in areas such as cartography and environmental monitoring, but the interpretation is more difficult because of the presence of speckle noise. Also, the way radar interacts with vegetation and the ground is not yet fully understood. However, the properties of the speckle noise are known, which helps in constructing suitable processing methods.

  In §2.2.2, the log transform was introduced, which ensures that the speckle variance is constant throughout the image. In chapter 3, a variety of smoothing filters were tried, including the moving median (§3.3.1) and spatially-adaptive filters (§3.3.2). Filters which make use of our knowledge of the speckle variance were also considered: the Wiener filter (§3.2.3) and Lee's filter (§3.3.2).

  In chapter 4, three ways were explored for segmenting the image into separate fields. In §4.1.3, contextual classification was used to segment the image into bright and dark fields using postclassification smoothing (Fig 4.9(b)) and an ICM algorithm (Fig 4.9(c)). In §4.3, a split-and-merge algorithm divided the image into regions for which the variance of pixel values was less than a specified limit. For other approaches to smoothing and segmenting SAR images, see Durand, Gimonet and Perbos (1987) and Oliver (1991).

- **Soil aggregate**: Fig 1.6(c) shows a cross-section of a soil aggregate, imaged by electron

microscopy. It was obtained in order to study the properties of the pores in the soil material.

In §4.1, manual and automatic thresholding methods were used to recognise which pixels belong to the pore space. The result is quite rough, so a morphological closing was used to reduce the noise (Fig 5.1(b)). In §5.2, a distance transform was used to measure an important property of pore space, namely the distribution of distance from the soil material. The use to which this can be put in modelling pore structure is beyond the scope of this book: see Glasbey, Horgan and Darbyshire (1991) and Horgan and Ball (1994). For other recent work on pore structure, which examines its fractal nature, see Bartoli, Philippy, Doirisse, Niquet and Dubuit (1991) and Young and Crawford (1991).

- **Turbinate bones**: This image is shown in Fig 1.2(a). A manually enhanced version, using black ink and typists' correction fluid, is shown in Fig 1.2(b). The aim was to measure the ratio of air-space-area in the cross-section of the nasal cavities to air-space-area plus turbinate-bone-area.

  In §5.2, a morphological closing was used to remove much of the irrelevant speckle which had resulted from the 'printing' described in §1.1.1. Manual intervention was required to separate the turbinate bones from the remaining bone areas, after which calculation of the morphometric index was straightforward (§6.2). Although a fully automatic algorithm would be desirable, what we describe here is a big improvement over the approach originally used.

- **Ultrasound**: An ultrasound image of a cross-section through a sheep's back is shown in Fig 1.7(d). The aim was to estimate depths of fat and muscle tissue. The features of this image proved too irregular, and too much affected by irrelevant artifacts of the image capture to allow a successful segmentation or classification based on the methods described in this book. A manual segmentation was required, after which the measurement of properties of the image is straightforward (§6.1.2). More complex manipulation of the pixel values is needed, using methods akin to the Hough transform, to find the boundaries automatically — see Glasbey, Abdalla and Simm (1996).

- **X-ray CT**: Fig 1.7(c) shows an X-ray computed tomograph of a sheep. Tomographic reconstruction of images from projections is not covered in this book (see, for example, Rosenfeld and Kak, 1982, chapter 8). The reason for collecting the image was to estimate areas of fat and lean tissue.

  In §2.2.2, a piecewise linear transform was used to make it easier to see differences in tissue type. The image was used extensively in chapter 3 to illustrate different linear filters (§3.1) and non-linear smoothing (§3.3) and edge-detection (§3.4) filters, and to demonstrate the information content of the amplitude and phase of the Fourier transform (§3.2.1), as well as the effects of constructing filters in the frequency domain (§3.2.3).

  After thresholding, a morphological opening was used in §5.2 to obtain a smooth outline for the eye-muscles in the image, which were then measured in §6.1.2. It was also shown how Feret diameters and shape statistics (§6.2) could be obtained. The boundary curvature was estimated (Fig 6.1(c)) and the concept of a convex hull illustrated (Fig 6.6). In general, similar algorithms are applicable to MRI and to X-ray CT images.

The above discussion illustrates a wide variety of aims and solutions. Techniques have been drawn from the different stages of image analysis, *Display, Filtering, Segmentation, Mathematical Morphology* and *Measurement*, as appropriate. The success achieved using the methods covered in the book has varied. For example, the aims have been completed with the fungal hyphae and algal images; some more refinement is needed with the SAR and muscle fibres images; and considerably more work is needed with the ultrasound and electrophoresis images.

The material covered in this book will not enable our readers to solve all the image analysis problems they may encounter. Rather, we hope that it lays a foundation of the main ideas on which the subject is built. If the reader wishes to go further, there are many excellent, more advanced books and journals which can be consulted. Their content should be more comprehensible after study of our book. The literature continues to increase, and we expect image analysis techniques to continue to grow in power and utility.