

Good Practice Guide No. 39

Dimensional Measurement using Vision Systems

Tim Coveney



Measurement Good Practice Guide No. 39

Dimensional Measurement using Vision Systems

Tim Coveney

Engineering Measurement Division
National Physical Laboratory

ABSTRACT

This guide provides information on the components that make up vision systems used for microscopic and macroscopic dimensional measurements. It also includes generalized measurement good practice and describes the various processes and techniques required to perform accurate and traceable dimensional measurements using these systems.

© Queen's Printer and Controller of HMSO, 2014

July 2001
Updated August 2014

ISSN 1368-6550

National Physical Laboratory
Hampton Road, Teddington, Middlesex, TW11 0LW

Acknowledgements

The author acknowledges the following contributions to this guide.

Gordon Roger who wrote the first edition of this guide; David Flack and Michael McCarthy for their assistance in this revision; UKAS for their valuable input to the project; all lead users who reviewed early drafts of this guide and last but not least the Department of Business, Innovation and Skills (BIS) for funding production of this guide as part of the 1999-2002 Length Programme (Project MPU 8/61.3). The latest updates were funded by the UK National Measurement System Programme for Engineering & Flow Metrology.

Contents

Introduction.....	1
What this guide is about and what it is not.....	2
Introduction to vision systems.....	2
Vision system components.....	3
Image formation and sensing	4
Image processing.....	4
Communication	4
Microscopy.....	5
Image formation and resolution.....	6
Aberrations in the image forming system	9
Spherical aberration.....	9
Chromatic aberration.....	9
Coma and astigmatism	10
Curvature of field	10
Optical components of the microscope	11
The microscope objective.....	11
Achromatic objective	12
Apochromatic objective	13
Flat field objective.....	13
Objectives with freedom from lateral chromatic aberration	13
Biological and metallurgical objectives	13
Tube length.....	14
Other objective parameters.....	14
The microscope eyepiece	15
Interchangeability of eyepieces and objectives	17
The microscope condenser	18
The concept of coherence.....	19
Optimal microscope use	22
Kohler illumination	23
Setting up procedure.....	26
Imaging microscopic features on large samples.....	29
Chapter summary.....	30
Macroscopy.....	33
Illumination sources for macro vision systems	34
Halogen lamps.....	34
Xenon strobe lamps.....	35
Fluorescent tubes.....	35
LED lighting.....	35

Lasers	35
Illumination configurations	35
Diffuse front lighting.....	36
Directional front lighting.....	36
Ring lighting.....	37
Back lighting	39
Selection of appropriate lighting configurations.....	39
Chapter summary.....	40
Lens configurations for macroscopic systems	41
Optical principles.....	42
The f-number.....	42
Thin lens formulae	43
Depth of field	44
Modulation transfer function.....	47
Aberrations in the image forming system	47
Lens selection and mounts.....	48
Commercial lenses.....	48
Standard lenses	48
High resolution lenses	48
Macro lenses.....	49
Telecentric lenses	49
Chapter summary.....	49
Cameras	51
Linearity of sensitivity response.....	52
Data transmission	52
Analogue cameras for vision systems	53
Interlaced (or synchronous) cameras.....	53
Progressive scan cameras	53
Asynchronous cameras.....	53
Digital cameras for vision systems.....	54
Linescan cameras.....	54
Chapter summary.....	54
Frame grabbers.....	55
Analogue frame grabbers	56
Live mode.....	56
Acquisition mode	56
Use with a standard video camera.....	56
Use with a progressive scan camera.....	56
Use with an asynchronous camera	57
Use with a line scan camera	57

Digital frame grabbers	57
Chapter summary.....	57
Making measurements.....	59
Basic Precautions.....	60
Choosing the right type of measurements	60
Capturing a good image.....	60
Obtaining the pixel calibration	61
Setting the correct detection threshold	62
Quantifying the effects of distortion and magnification errors	64
Sources of measurement uncertainty.....	65
Chapter summary.....	70
Summary.....	71
Glossary of terms	73
Glossary of terms.....	74
Health and safety.....	75
Mechanical hazards	76
Hazards associated with laser illumination	76
Chemical hazards.....	76
Appendices.....	77
 Appendix A Links to other useful sources of information	 78
A.1 National and International Organisations.....	78
A.1.1 National Physical Laboratory	78
A.1.2 National Institute of Standards and Technology (NIST)	79
A.1.3 EURAMET	80
A.1.4 Institute for Geometrical Product Specification	80
A.2 Networks	81
A.2.1 Mathematics and Modelling for Metrology (MMM)	81
A.3 National and International Standards	81
A.3.1 British Standards Institution (BSI)	81
A.3.2 International Organisation for Standardization (ISO)	81
A.4 Traceability	82
A.5 Training courses	83
A.5.1 Dimensional Measurement Training: Level 1 – Measurement User...	83
A.5.2 Dimensional Measurement Training: Level 2 - Measurement Applier	84
A.5.3 Mitutoyo training courses	86
A.5.4 NPL E-Learning.....	86
 Appendix B Further reading	 88

List of Figures

Figure 1: Mitutoyo Hyper QV 606 PRO/TP Vision System.	3
Figure 2: Airy disc intensity pattern.	7
Figure 3: Intensity sum of two airy patterns.	7
Figure 4: Spherical aberration.....	9
Figure 5: Chromatic aberration.....	10
Figure 6: Image formation in the microscope.....	12
Figure 7: The Huygens eyepiece.....	17
Figure 8: The Ramsden eyepiece.....	17
Figure 9: Interference due to temporal coherence.	20
Figure 10: Image intensity profile at a sharp edge.....	21
Figure 11: Features of a microscope.....	22
Figure 12: Ray paths for critical illumination.....	24
Figure 13: Ray paths for Kohler illumination.....	25
Figure 14: Image intensity profile of an edge in incoherent and coherent light.	26
Figure 15: Condenser diaphragm set at 2/3 diameter of the objective pupil.	28
Figure 16: Schematic of a programmable power turret system.	30
Figure 17: Macro image processing system.....	34
Figure 18: Diffuse front lighting.....	36
Figure 19: Directional front lighting.....	37
Figure 20: Ring light illumination.	38
Figure 21: Back light illumination.....	39
Figure 22: Lens relative aperture.	42
Figure 23: Image formation by a thin lens.....	43
Figure 24: Circle of confusion.	45
Figure 25: Image distortion.....	47
Figure 26: Selecting the correct lens/CCD sensor format.	48
Figure 27: Normal and saturated image illumination.	61
Figure 28: Calibrating the image pixel size.	62
Figure 29: Intensity profile of a dark line on a bright background.....	63
Figure 30: Comparison of average intensity profile with a single pixel line intensity profile.	64
Figure 31: NPL's ODS, which contains patterns specifically designed to identify and quantify errors in a range of optical systems.....	65
Figure 32: Calibration offsets, with the coefficients of the linear fit displayed.	66

Dimensional Measurement using Vision Systems

Preface

The author hopes that after reading this Good Practice Guide you will be able to better understand dimensional measurement using vision systems. The content is written at a simpler technical level than many of the standard textbooks so that a wider audience can understand it. I am not trying to replace a whole raft of good textbooks, operator's manuals, specifications and standards, rather present an overview of good practice and techniques.

GOOD MEASUREMENT PRACTICE

NPL has defined six guiding principles of good measurement practice. They are:

1. **The right measurements:** *Measurements should only be made to satisfy agreed and well-specified requirements.*
2. **The right tools:** *Measurements should be made using equipment and methods that have been demonstrated to be fit for purpose.*
3. **The right people:** *Measurement staff should be competent, properly qualified and well informed.*
4. **Regular review:** *There should be both internal and independent assessment of the technical performance of all measurement facilities and procedures.*
5. **Demonstrable consistency:** *Measurements made in one location should be consistent with those made elsewhere.*
6. **The right procedures:** *Well-defined procedures consistent with national or international standards should be in place for all measurements.*

You can make a significant difference to your measurement capabilities by simply following these principles, which should all be part of your own quality system.

Introduction

1

IN THIS CHAPTER

- What this guide is about and what it is not
- Introduction to vision systems

This measurement good practice guide provides an overview of dimensional measurement using Vision Systems. It is an update to a guide first published in 2001 and has been updated to reflect changes in the standards and improvements in technology over the last ten years.

What this guide is about and what it is not

It is intended that this guide should give enough information so that the metrologist can make measurements with a Vision Metrology system. This may be a 1-, 2- or 3-dimensional system and may take many forms. However all such systems have several key components in common and this guide covers good practice regarding illumination, lens and camera selection which will be applicable to the selection of appropriate systems and their use in day-to-day metrology.

This guide will not in general make direct comparisons between systems produced by different manufacturers, nor will it provide specific advice on which technologies are most suited to which application. This is simply because it could not be hoped to cover all areas of interest. Instead it will focus on an introduction to the basics of the optical and electrical systems that underpin all Vision Metrology so that the metrologist may have the necessary knowledge to make an analysis for themselves.

Introduction to vision systems

Vision systems (figure 1) are used in a wide range of industrial and scientific applications from biological and medical imaging to high-speed inspection and optical character recognition. The properties measured in these applications are diverse and for example can be the size, shape, colour, quantity, density etc. of the objects being viewed.

This guide focuses on the use of vision systems for dimensional measurement only and does not attempt to cover any of the aforementioned application specific measurement areas. It provides information on the components that make up vision systems used for microscopic and macroscopic dimensional measurements, and generalized measurement good practice advice that is applicable to all vision systems used for dimensional measurements. Readers new to the field, who are looking for more comprehensive information on the technology and applications of vision systems and image processing as a whole, are referred to the publications listed in Appendix B.

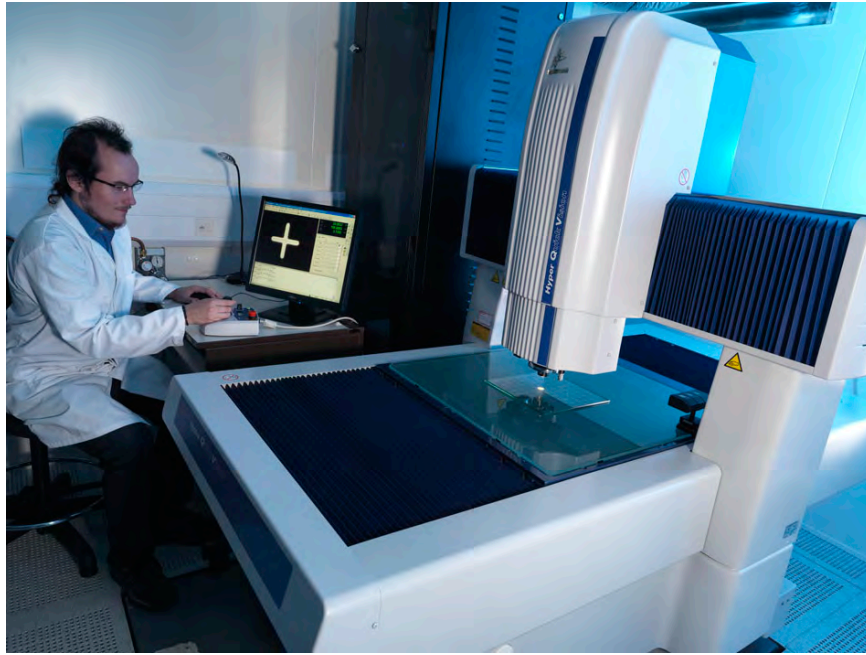


Figure 1: Mitutoyo Hyper QV 606 PRO/TP Vision System.

Figure 1 shows a typical vision system designed for dimensional measurement. When compared to conventional contact type inspection and measurement methods, non-contact measurement using vision systems offers a number of advantages, some of which are listed below.

- Accurate measurements can be obtained from thin or soft work pieces; and brittle, elastic or moving parts can be measured accurately and quickly, as the measurement technique is neither invasive, nor destructive.
- It is possible to measure precisely fabricated components and features that cannot be accessed by conventional contact type machines and gauges.
- Quality control and real time feedback can be readily integrated into the manufacturing process.

It should however be noted that vision systems are not a panacea for all inspection requirements and initial capital costs may well be high when integrating a vision system into a production or inspection process. Careful consideration must also be given to the selection of the correct type of inspection method for a particular process or product.

Vision system components

In its most basic form, a vision system consists of optical and electronic components to achieve three processes: image formation and sensing, image processing and communication.

Image formation and sensing

All vision systems use some form of light source to illuminate the object being measured. Without an effective illumination source, information on the workspace may be missed or recorded with poor quality. This is a critical area of the measurement system, since the quality of the original data determines the quality of the final result.

There are two ways of illuminating an object. The first is to transmit light through or around it and the second is to reflect light off it. Both are very much application dependant, but the rule of thumb, when performing dimensional measurements, is to choose the type of illumination that will give the best contrast between the object and the background and provide an even field of illumination. A range of illumination sources is available and is described in more detail in chapter 3.

The illuminated object is then imaged on to a detector, which is usually a CCD (Charged Coupled Device) camera, by a suitable optical arrangement. Various optical configurations and image sensors are described in chapters 4 and 5, respectively.

Image processing

Once the object of interest has been imaged correctly, measurements can be made. For this, some form of computer or microprocessor is required to process the image detected by the camera. A frame grabber, controlled by proprietary vision system software, is normally used to read the digitised image from the camera. Once the image is captured, it can be processed, with measurements being made using functions and algorithms in the vision system software.

Communication

The final process is to communicate the results of the measurements to the operator. The most common and simplest method is to display graphically the image and any measurements performed, on a monitor. However, this is generally not sufficient for vision systems that are integrated into a manufacturing process. With these systems, it may be necessary to output the measurements to other devices, such as Programmable Logic Controllers (PLCs), which are used for in-process control, or to file storage devices, so that the information can be retrieved for use at a later time. The ability to provide real time feedback into a process is one of the main advantages of vision systems.

In configuring a vision system there are many different combinations of image formation, sensing and processing components and techniques available. Each system is therefore likely to have unique components to perform the task required of it. The following sections will describe the more common methods and devices used by vision systems to achieve these three key processes.

Microscopy

2

IN THIS CHAPTER

- Image formation and resolution
- Aberrations in the image forming system
- Optical components of the microscope
- The microscope objective
- The microscope eyepiece
- Interchangeability of eyepieces and objectives
- The microscope condenser
- The concept of coherence
- Optimal microscope use
- Imaging microscopic features on large samples
- Chapter summary

Vision systems designed for measuring microscopic* objects are likely to use an optical microscope or similar high-powered lens arrangement. In order to make accurate dimensional measurements with such equipment it is advantageous to have an understanding of not only how the microscope produces an image, but also of the associated illumination equipment and the limitations to the measurement caused by the nature of light. *Note - for the purposes of this guide, objects less than 1 mm in size will be classed as microscopic and objects greater than 1 mm, macroscopic.

Image formation and resolution

It is well known that, due to diffraction, the image of an infinitely small point source, *e.g.*, a distant star, formed by a well corrected lens system is not infinitesimal, but has a finite size, and takes the form of a bright central disc (the so called Airy disc) surrounded by rings of rapidly decreasing intensity. The intensity distribution across this Airy pattern is shown in figure 2, the radius r of the first intensity minimum being given by

$$r = \frac{0.61\lambda}{NA}, \quad (1)$$

where λ is the wavelength of light emitted by the point source and NA is the numerical aperture of the imaging system.

The same effect occurs when using a microscope to view a very small object. Here the object is not self-luminous but is illuminated by a light source producing radiation of wavelength λ . The numerical aperture of the imaging system, the microscope objective in this case, is equal to the product of the refractive index of the object space and the sine of the semi-angle of the cone of rays entering the objective. For high precision dimensional measurements 'dry' objectives are invariably employed (as opposed to immersion objectives) and the object space refractive index is unity.

Because of the finite size of the Airy disc the microscope has limited resolution *i.e.* there is a minimum separation of two object points that allows the images to be resolved. The commonly adopted criterion for resolution assumes that two objects can just be resolved when the centre of one Airy disc image falls on the first minimum of the other *i.e.* the limit of resolution is equal to the radius r of the Airy disc as given in equation (1). It should be stressed that the resolution limit defined in this manner is an arbitrary one.

At this separation of two points, the direct addition of two Airy disc intensity curves will be as shown in figure 3, with a 26.6 percent reduction in intensity at the mid-point between the two discs. This drop in intensity should be readily detectable by the eye. However, if a photoelectric system is employed that can detect a significantly smaller drop in intensity, the two-point resolution of the microscope could be considered as being rather better than that given by equation (1).

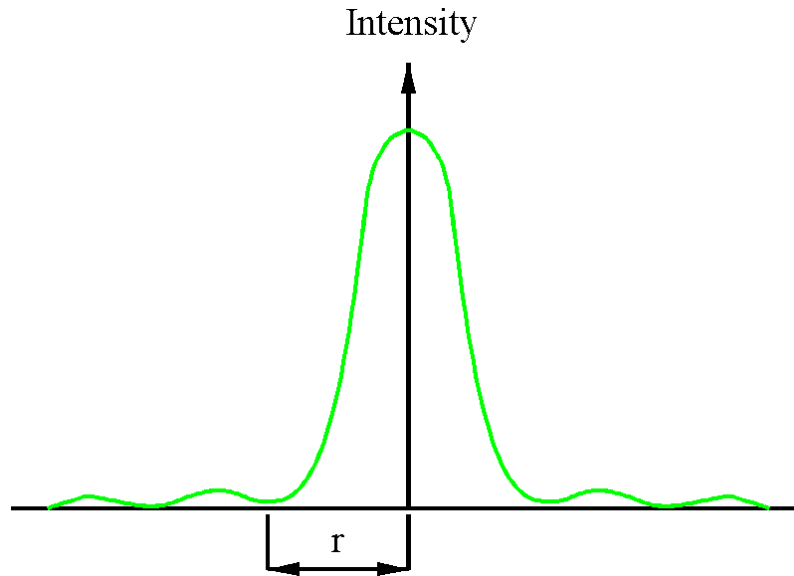


Figure 2: Airy disc intensity pattern.

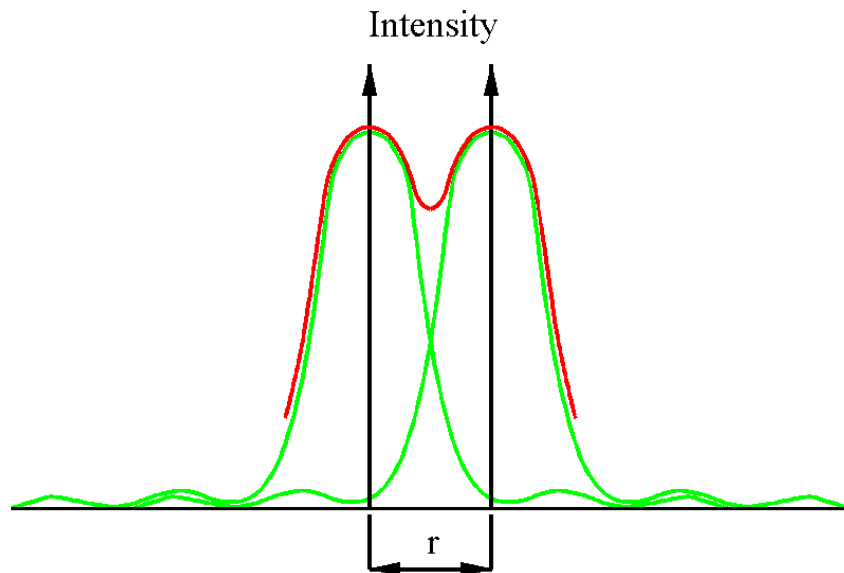


Figure 3: Intensity sum of two airy patterns.

It will be seen later that other factors, including the coherence of the light, and the numerical aperture of the condenser must also be considered in assessing resolution. Nevertheless, expression (1) gives a reasonable guide to the resolution that can be expected from a microscope objective working under normal conditions.

Equation (1) shows that the minimum resolvable object separation decreases with increasing objective numerical aperture. Resolution figures derived from this expression for typical microscope objectives are shown in table 1 (assuming green light illumination of wavelength 550 nm).

Table 1 Objective resolution limit

NA	Magnification	Resolution / μm
0.1	5×	3.36
0.5	20×	0.67
0.65	40×	0.52
0.9	100×	0.37
1.25*	100×	0.27

*Immersion objective

Knowing the resolution limit of the objective, it is then possible to determine the overall magnification of the microscope (*i.e.*, the combination of the objective and eyepiece magnifications) necessary to allow this limit to be resolved by an observer either by direct visual observation or, for example, by viewing on a TV screen.

In the case of direct visual observation it is known that the human eye is capable of resolving two objects when their angular separation is at least one minute of arc. Assuming the minimum distance for viewing an object by the unaided eye to be 250 mm, the corresponding minimum resolvable object separation will be approximately 0.07 mm. This represents the absolute minimum value and, in practice, for comfortable viewing a minimum object separation of, say, 0.4 mm should be used. Based on this limit, the useful overall magnifications for various objectives are shown in table 2.

Table 2 Useful microscope magnification

NA	Objective	Overall Magnification
0.1	5×	120
0.25	10×	300
0.5	20×	600
0.65	50×	770
0.9	100×	1080
1.25*	100×	1480

*Immersion objective

The figures in table 2 should only be regarded as approximate, as under certain conditions somewhat larger magnifications may be required to reduce observer fatigue.

For TV projection viewing, assuming a 25 cm high, 625-line display, the line separation will be 0.4 mm and the magnifications listed in table 2 will again provide useful guide figures. If the overall magnification of the microscope is increased much beyond these values, existing features in the image will become larger but without further detail being made visible to the eye. This 'non useful' magnification is usually referred to as empty magnification.

The limit of magnification by visual optical microscopy has now almost been reached. From equation (1) it will be seen that decreasing the illumination wavelength λ can reduce the minimum object separation resolvable by a microscope objective. However, in terms of optical microscopy the minimum useful wavelength is around 300 nm in the ultraviolet (UV)

region of the spectrum and this only produces a resolution improvement of around $\times 2$. It also brings with it the added complexity that specially designed optics have to be employed in the UV.

A more significant improvement can be achieved by using a scanning electron microscope. Although the numerical apertures of electron lenses are very limited, the effective wavelength of the electron beam is extremely small and a resolution limit of 10 nm (0.01 μm) or even less is readily achievable, a figure at least thirty times smaller than achievable with an optical microscope. Thus, in the future, with the ever-decreasing size of microelectronic structures, the use of electron microscopy will inevitably become more widespread.

Aberrations in the image forming system

The intensity distribution in the Airy pattern, shown in figure 2, will only be produced by a lens of perfect quality. In practice, defects in the lens performance will result in some redistribution of the energy, usually leading to degradation in image quality and to errors if the system is employed for making dimensional measurements. These defects are known as aberrations and can be divided into the following types.

Spherical aberration

If, after passing through different parts of the lens aperture, the rays of light from a single object point are focused in different image planes, the lens is said to exhibit spherical aberration (see figure 4). With increasing spherical aberration in a lens, the intensity of the central disc of the diffraction pattern gradually decreases, accompanied by more light in the surrounding rings. This results in reduced image contrast and resolution. Although microscope objectives are usually well corrected for spherical aberration, some may easily be introduced by using incorrect working conditions *e.g.*, the wrong tube length (see chapter 2).

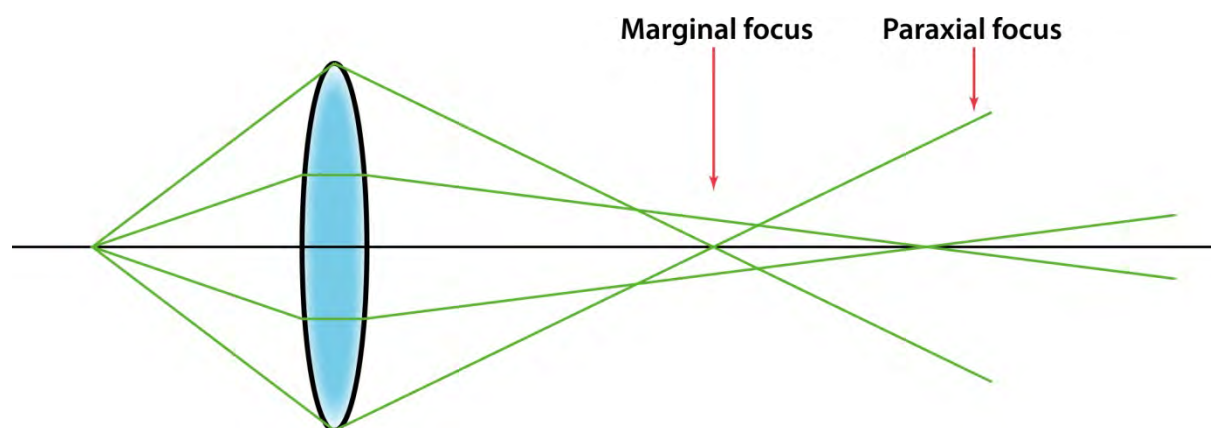


Figure 4: Spherical aberration.

Chromatic aberration

If rays of different colours are focused in different image planes, the lens is said to exhibit longitudinal chromatic aberration (see figure 5). In addition, some lenses, for example complex microscope objectives, give images with slightly different magnifications for light

of different colours. This defect is known as transverse or lateral chromatic aberration and will be considered in more detail in chapter 2. In metrological applications, microscope objectives are usually used with filtered illumination so that the effect of any residual chromatic aberration is minimised.

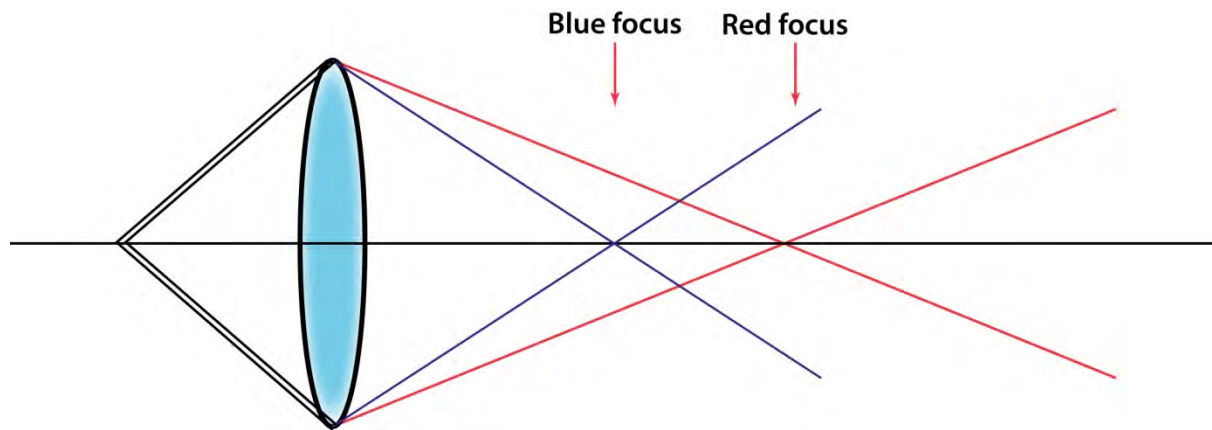


Figure 5: Chromatic aberration.

Coma and astigmatism

Whereas spherical and longitudinal chromatic aberrations can occur over the whole object field, coma and astigmatism are essentially off-axis aberrations. In the presence of coma, a point object is imaged with a radially oriented flare. Astigmatism in a lens causes a point object to be imaged as two short lines at right angles to each other and in slightly different focal planes. The appearance of coma or astigmatism at the centre of the image field indicates mechanical rather than design faults in the objective, *e.g.* a centring defect.

Curvature of field

Field curvature in an objective causes a plane object to be imaged on a curved surface. Thus, the whole field of view of the objective will not be sharply defined at one focus setting; however, provided the objective is free from other off-axis aberrations, the whole field can be critically examined by making slight changes in the focus setting.

Image distortion, *i.e.* a gradual change in magnification from the centre to edge of the image field causes a square object to be imaged with the characteristic 'barrel' or 'pincushion' shape. Microscope objectives commonly exhibit some distortion (typically of the order of one percent), but this may not be apparent in the observation of many types of object. However, if dimensional measurements are to be made directly from the microscope image and over a large field of view, the performance of the objective and eyepiece system should be checked in this respect using a stage micrometer or other type of graticule.

Optical components of the microscope

In very basic terms, the optical system of a microscope consists of an objective forming the primary image of the object and an eyepiece producing a secondary virtual image, which is then viewed by the eye (see figure 6). For relaxed viewing, the focusing may be adjusted so that the virtual image is effectively at infinity. The condenser illuminates the object, with the objective itself acting as condenser in most reflected light microscopy. Microscope manufacturers produce several different types of each of these components and it is therefore useful to summarise their respective properties.

The microscope objective

The microscope objective is the most critical component of the optical system. Ideally this lens should produce a well-defined image with any residual spherical aberration, coma and astigmatism minimised to ensure that it is capable of resolving the theoretical limit discussed earlier in chapter 2. In addition, the image should be substantially free from curvature of field and distortion and with excellent colour correction to allow a wide illumination bandwidth to be used. Microscope objectives are generally classified according to their colour correction with an additional reference if they are of the flat field variety. The complexity of the objective, *i.e.*, the number of component lenses it contains increases with its numerical aperture and with the overall state of correction required; a high power dry objective may contain ten or more component lenses in order to achieve a high degree of optical correction over a large field.

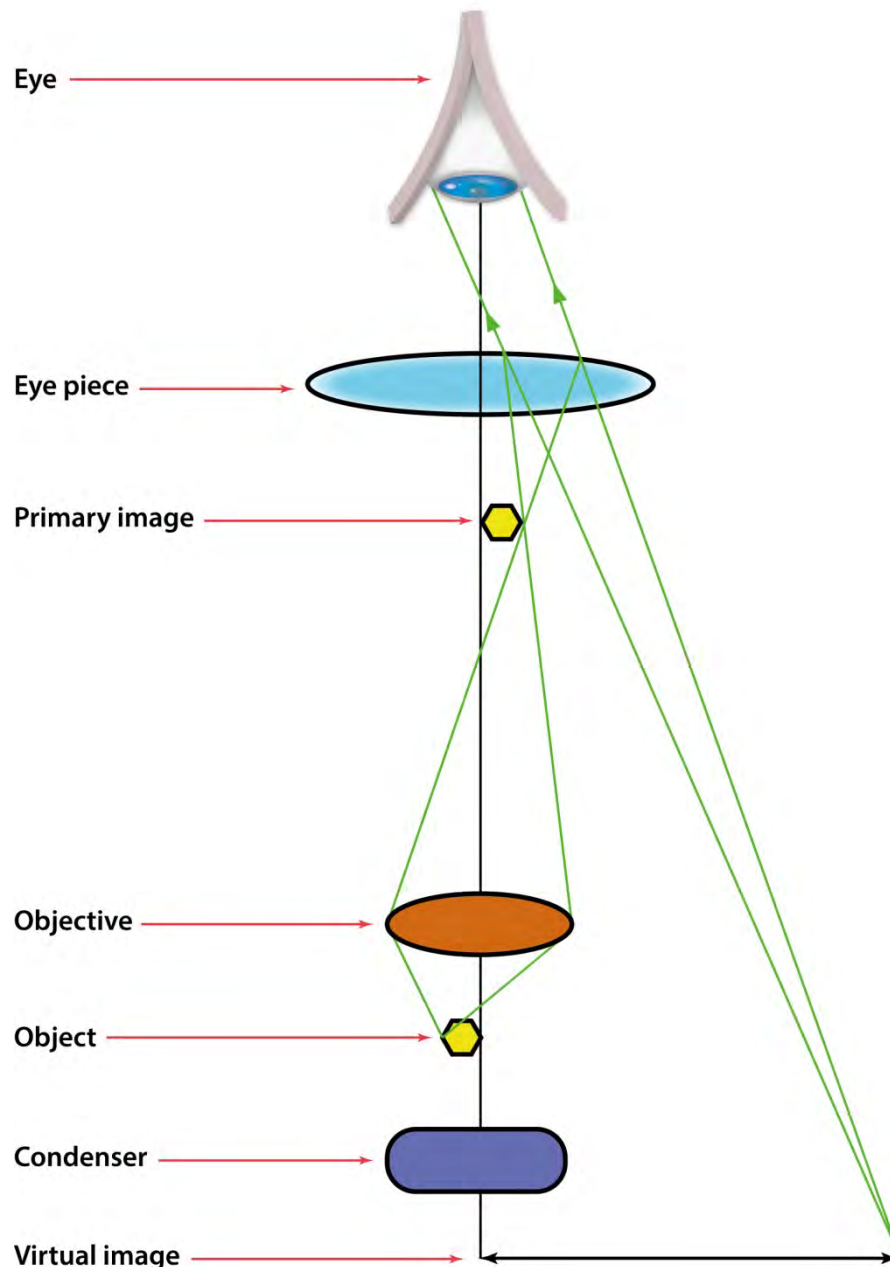


Figure 6: Image formation in the microscope.

Achromatic objective

The achromatic objective is the type most commonly used in microscopy and is capable of giving good image quality at relatively low cost. It is designed so that light of two specified wavelengths, one in the red and the other in the blue region of the spectrum, comes to a common focus, there being some residual chromatic aberration (usually known as secondary spectrum). Image performance of an achromat is likely to be best in green light and appropriate filtration of the illumination is therefore desirable. The simplest types of achromatic objective produce an image with some curvature of field.

Apochromatic objective

In this type of objective, which is of a more complex design and uses a wider range of optical materials than the achromat, light of three different wavelengths is brought to a common focus. The colour correction of the apochromat is significantly superior to that of the achromat and indeed, over the centre of its field the overall standard of performance is extremely high. The cost of an apochromat is usually several times that of an achromat of comparable numerical aperture.

As a compromise between these two objective types, objectives known as 'fluorites' or 'semi-apochromats' are available from most manufacturers. These contain fewer optical components than the true apochromat and are correspondingly cheaper; their performance is somewhat superior to that of the achromat.

Flat field objective

Field curvature of the image is obviously extremely undesirable when an objective is being used for photomicrography or for dimensional measurements. Unfortunately, ordinary achromat and apochromat objectives suffer from curvature of field, which tends to become more marked as the objective power increases. Flat-field objectives (frequently designated 'plan' objectives) were therefore developed to overcome this limitation; they are available with achromatic, fluorite or apochromatic correction but, in general, their chromatic correction is somewhat poorer than that of the 'curved field' design.

Objectives with freedom from lateral chromatic aberration

Many types of microscope objective possess transverse chromatic aberration, *i.e.* the image magnification produced by the objective is slightly wavelength dependent, being greater for blue light than for red. Images of objects near the edge of the field will then exhibit slight colour fringing, a dark object having a red fringe on its outer side and a blue fringe on its inner side. Most high power objectives ($\times 40$ and over) and almost all flat-field objectives exhibit some transverse chromatic aberration and this is corrected by using a compensating eyepiece specially designed to offset the objective aberration. Newer designs of microscope objectives are available where transverse chromatic aberration has been corrected independently in both the objective and eyepiece, leading to excellent colour correction over the whole field of view. A compensating eyepiece should obviously not be used with this type of objective.

Biological and metallurgical objectives

Biological specimens are usually examined with the sample covered by a glass coverslip 0.17 mm in thickness. This thin parallel-sided plate will itself introduce spherical aberration, which must be compensated for in the objective design. In contrast, in the metallurgical and microelectronics fields, no coverslip is usually employed. Manufacturers therefore offer two series of objectives, one for biological and the other for metallurgical applications. As the spherical aberration introduced by the coverslip increases rapidly with the obliquity of the light rays, deterioration of image quality becomes more marked at higher numerical apertures if the wrong type of objective is employed. For numerical apertures of 0.35 or lower, the

choice of objective type is not critical and, in fact, manufacturers generally produce only one series of low power objectives.

Tube length

All lens systems are designed to operate with specific object and image distances and their performance will only be optimum at these conjugates. Microscope objectives are conventionally designed for a mechanical tube length of 160 mm; this represents the distance between the objective and eyepiece shoulders in the microscope body and thus defines the distance between the objective and the image it produces. The choice of this dimension dates back to the time when microscope bodies were of the straight tube monocular type. With the widespread use of inclined binocular heads, the mechanical tube length has had to be increased above 160 mm, but an auxiliary lens permanently located within the microscope body ensures that objectives still function under optimum conditions. It should be noted that this auxiliary lens increases the overall magnification of the microscope.

With older monocular microscopes, the length of the body tube was frequently adjustable allowing, for example, some compensation for the aberration introduced by the use of a coverslip of the wrong thickness. Modern microscopes, in general, do not possess this body tube adjustment. It should be noted that although most modern microscope objectives are still designed for a mechanical tube length of 160 mm, some manufacturers favour other tube lengths or even an infinite image conjugate. These objectives must obviously only be employed in microscopes specifically designed for their use.

Other objective parameters

An important objective parameter is its depth of field, *i.e.* the object depth that is sharply defined at one focus setting of the objective. Obviously only a single plane will be in best focus and figures for the depth of field will depend on the criterion adopted for the acceptable loss of image definition. One criterion is based on a quarter of a wavelength of path difference between the axial and marginal image forming rays being considered permissible and leads to the following expression for the depth of field df :

$$df = \frac{\lambda}{4N \sin^2 \left(\frac{U}{2} \right)}, \quad (2)$$

where N is the refractive index of the object space and U the angle between the marginal ray and microscope optical axis. Values evaluated from this expression are listed in Table 3 and clearly illustrate the very limited depth of field of high power objectives.

The working distance of a microscope objective, *i.e.* the distance between the object (or upper surface of the coverslip for a biological objective) and the front of the objective mount varies with objective design, but typically falls within the ranges listed in Table 3. Some objectives are produced with especially long working distances, for example up to 3 or 4 mm for an objective of 40× power.

A series of objectives mounted in a revolving nosepiece is invariably designed to be parfocal *i.e.* with each objective in position the image is so nearly in focus that only slight adjustment

of the focus control is necessary. Current and older objectives from a given manufacturer may not be parfocal, nor will, in general, objectives produced by different manufacturers. There are, however, proposals to standardise the distance between the front shoulder of the nosepiece and the object plane.

Considering the number of parameters relating to objectives, it is perhaps not surprising that the marking of data on objective mounts has still to be standardised. Objective magnification and numerical aperture are two factors that are always marked; additional data may refer to the state of chromatic correction of the objective if it is of fluorite or apochromatic type and to the flatness of field, and also include values of tube length and cover slip thickness for which the objective has been designed.

Table 3 Some objective parameters

NA	Magnification	Colour	Depth of field / μm	Working distance /mm
0.1	5 $\times$	Red	55	10 - 15
0.25	10 $\times$	Yellow	8.7	5 - 8
0.5	20 $\times$	Bright Green	2.1	0.9 - 1.6
0.65	40 $\times$	Light Blue	1.1	0.4 - 0.7
0.9	100 $\times$	White	0.5	0.1 - 0.2
1.25*	100 $\times$	White	0.4	0.1 - 0.2

*Immersion Objective

Objectives are colour coded according to their magnification and the colours of a currently well-used code are included in table 3. There may be a further marking for specialised objective types, for example, PH (phase contrast), POL (objectives with freedom from strain for use in polarizing microscopes) DIC (differential interference contrast) and DF (objectives for incident dark field microscopy). The marking 'OIL' is frequently to be found on immersion objectives.

The microscope eyepiece

Eyepieces are used either to form a virtual image, which is then viewed by the eye or a CCD camera, or to form a real image on a projection screen or photographic emulsion. For projection purposes most manufacturers produce special eyepieces, which are designed to produce images with minimum field curvature, but these are unsuitable for normal visual applications. However, standard types of eyepiece will usually give satisfactory performance when employed for photomicrography. If the eyepiece is located so that a virtual image is formed 25 cm from itself (*i.e.*, the least distance of distinct vision), then the magnification M it produces is given by:

$$M = \frac{25}{f} + 1, \quad (3)$$

where f is the focal length of the eyepiece in cm.

In practice, continuous viewing with the eye focused at 25 cm tends to be fatiguing and it is more common to view with the eye relaxed so that the image from the eyepiece is effectively at infinity. The magnification M' is then slightly different, being given by:

$$M' = \frac{25}{f}. \quad (4)$$

Eyepiece magnifications are usually within the range $\times 5$ to $\times 15$ and are quoted according to expression (4). The two basic types of eyepiece are the Huygens and the Ramsden, both designs consisting of two plano-convex lenses as shown in figure 7 and figure 8. The field stop in an eyepiece defines the overall field of view seen under the microscope and is located at an intermediate image plane. The Huygens eyepiece is designed so that the field stop is located between the two lenses and thus any graticule or crosshair at this plane will be observed through only the eye lens rather than through the complete eyepiece and its image will consequently not be aberration free. The Huygens eyepiece is well corrected for lateral chromatic aberration and is probably the best type of eyepiece to use with most ordinary achromatic objectives. The Ramsden eyepiece has its field stop in front of the field lens and is therefore better suited than the Huygens for measuring purposes. Filar eyepieces are usually of the Ramsden type.

The compensating eyepiece is in widespread use today; its design is more complex than the simple Huygens or Ramsden types, with lateral chromatic aberration being deliberately introduced to balance that occurring in many microscope objectives, (see chapter 2, Objectives with freedom from lateral chromatic aberration). Wide-field eyepieces are usually of the compensating type and are particularly useful for searching purposes in combination with flat field objectives. A wide field eyepiece with magnification $\times 10$ can have a field diameter as large as 20 mm and even larger fields are obtainable using special eyepieces and eyepiece tubes.

The exit pupil (or eye point) of an eyepiece is the image formed by the eyepiece of the objective pupil. It is typically located between 6 mm and 15 mm above the eye lens and represents the point at which the light rays through the microscope are concentrated to a very small bright spot. The eye must be positioned close to this eye point for the whole field of view of the microscope to be visible. Special 'high point' eyepieces are available with eye relief (*i.e.* distance from eye lens to eye point) of 20 mm to 30 mm and these should be used by observers wearing spectacles.

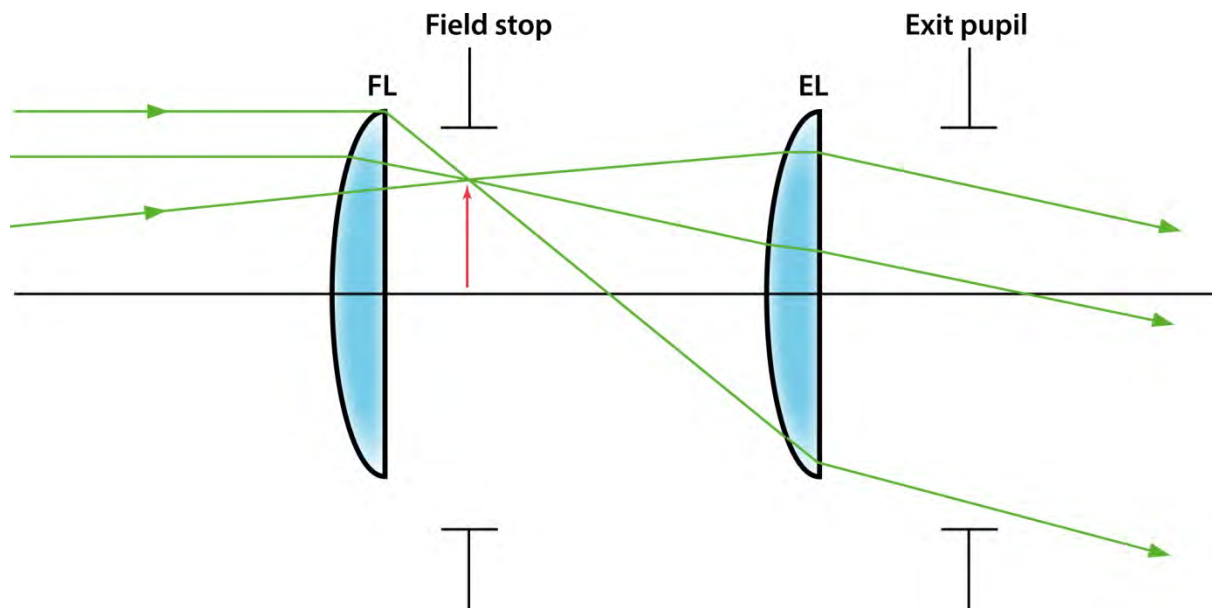


Figure 7: The Huygens eyepiece.

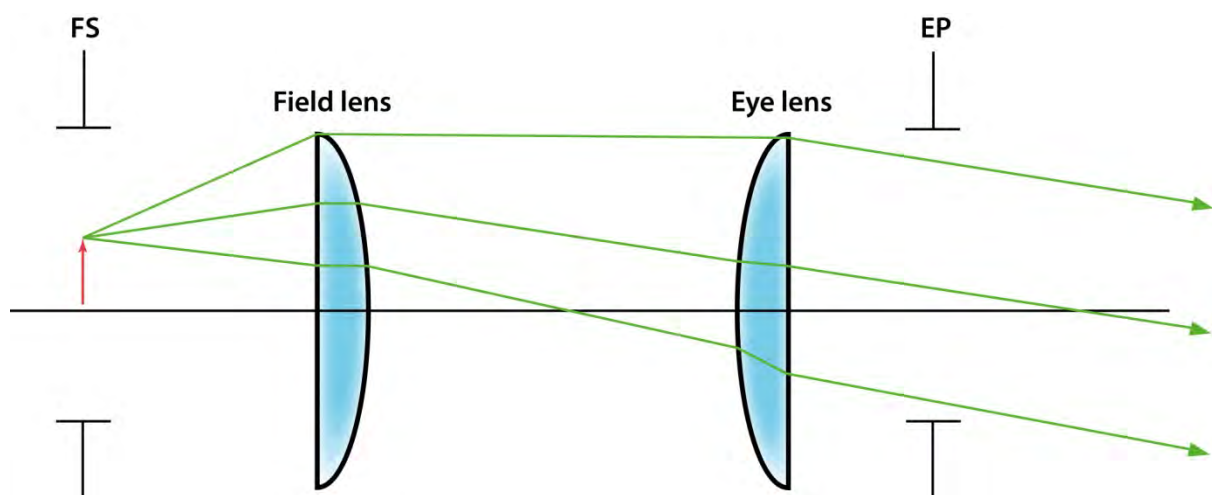


Figure 8: The Ramsden eyepiece.

Eyepieces produced by the same manufacturer are usually mounted so that they are parfocal. For microscopes with binocular heads eyepieces are normally provided in pairs, each pair being chosen for accurate concentricity and equal magnification.

Although eyepiece markings have still to be standardised, the magnification is always marked; additional information may include the field of view in mm and the type of eyepiece, for example, Hy (Huygens), Comp (Compensating) and WF (Wide Field).

Interchangeability of eyepieces and objectives

Due to the standard dimensions involved, the physical interchanging of objectives and eyepieces from one microscope to another presents no difficulties, even if these are of different makes. Thus, the objective mount has a standard thread (of Whitworth form)

originally specified by the Royal Microscopical Society. Almost all objectives conform to this thread, an exception being recent designs of dark field objective where the size of the mount has led to a larger thread diameter being adopted. The external diameter of the cylindrical eyepiece mount is nominally 23.2 mm and this value is almost universally adopted, except for a few ultra-wide field eyepieces.

However, this interchanging of components can easily lead to problems. If objectives of different manufacturers are used in the same revolving nosepiece, parfocality, with all its convenience, will probably be lost, and this may also occur with different makes of eyepiece. Interchanging may mean that objectives are operating at slightly incorrect conjugates, *i.e.* at effectively the wrong tube lengths, leading to deterioration of image quality particularly at higher powers. Results that are even more disastrous will be obtained if an objective corrected for an infinite conjugate is used in a microscope designed for a 160 mm tube length.

Summarising, it would seem that although the combination of objective, eyepiece and microscope body from three different manufacturers may give very acceptable performance, not all such combinations will be satisfactory, and the very best image definition is most likely to occur when all components are from the same manufacturer.

The microscope condenser

In transmitted light microscopy, the condenser provides a cone of light for illuminating the object. The numerical aperture of the condenser can be varied by means of an iris diaphragm and should have a maximum aperture comparable to that of the objective. As image quality in the microscope is far less dependent on the optical correction of the condenser compared with that of the objective, condensers are usually less complex in design.

One of the simplest types of condenser is the two-element Abbe, which has a high numerical aperture but is poorly corrected in terms of spherical and chromatic aberration. This can result in a non-uniform distribution of light into a high numerical aperture objective and also poor definition of the field stop, which is imaged by the condenser at the specimen level. The Abbe condenser is frequently designed so that its upper element can be swung out of the light beam or an extra lower element added; in this way a large object field can be illuminated for low power work.

By using three or four lens components, spherical aberration can be corrected (aplanatic condenser), while for the most critical work it is preferable to use an achromatic condenser. The latter produces a sharp image of the field stop and thus minimises stray light, which might otherwise reduce image contrast.

Condensers are conventionally designed with sufficient working distance for use with a standard microscope slide 1 mm in thickness. Glass photomask substrates are typically 1.5 mm or 2.3 mm in thickness and it is important to ensure that condensers used for illuminating these masks have adequate working distance.

In reflected light microscopy (apart from very low power work) the microscope objective itself acts as condenser. A beam splitter located above the objective directs light to the specimen and then after reflection allows the light to pass through to the eyepiece. Under

these conditions of illumination, image contrast can be seriously reduced by back reflections from the lens surfaces of the objective since spurious light is able to reach the eyepiece without taking part in the true image forming process in the microscope.

This effect can be reduced by means of antireflection coatings on the lens surfaces and these are now almost universally applied to microscope optics. With a single layer coating the reflectance at an air/glass interface is about 1.5 per cent, compared to a figure of 4 per cent for an uncoated surface. However, by the use of a multi-layer coating, this reflectance can be reduced to well below 0.5 per cent and multicoated objectives are therefore particularly recommended for reflected light microscopy.

The concept of coherence

To study image formation in rather more detail than in chapter 2, Image formation and resolution, it is necessary to introduce the concept of coherence and to consider the difference between temporal and spatial coherence.

Assuming light to be propagated as a transverse wave motion, a 'perfectly' monochromatic beam of light can be represented as consisting of a continuous train of waves, effectively of infinite length. Light from a helium-neon laser possesses an extremely narrow bandwidth and can be considered to conform reasonably closely to this model. In contrast, light emitted by more conventional sources, such as discharge and tungsten lamps, has a much broader bandwidth, even when interference filters are employed to isolate a narrow spectral range. The emitted wave trains can then be regarded as having a finite rather than infinite length, with no fixed phase relation existing between successive wave trains. The length of the wave trains will decrease with increasing illumination bandwidth.

Suppose a monochromatic beam is divided into two parts, with some of each part then recombining. This can occur, for example, in a thin film, where part of the incident wave is reflected at each surface of the film, as shown in figure 9. Because of the continuity of the wave train, the recombining waves 'a' and 'b' will have a constant phase difference and are therefore said to exhibit temporal coherence. The sinusoidal wave resulting from the combination of these two simple harmonic vibrations will have amplitude (and hence intensity - equal to the square of the amplitude) dependent on this phase difference. Thus, depending on the thickness of the film, constructive or destructive interference will occur, leading to brightness or darkness in the overall reflected beam (see figure 9). With white light illumination, different interference effects will occur at different wavelengths, resulting in colour fringes as commonly seen, for example, in soap bubbles.

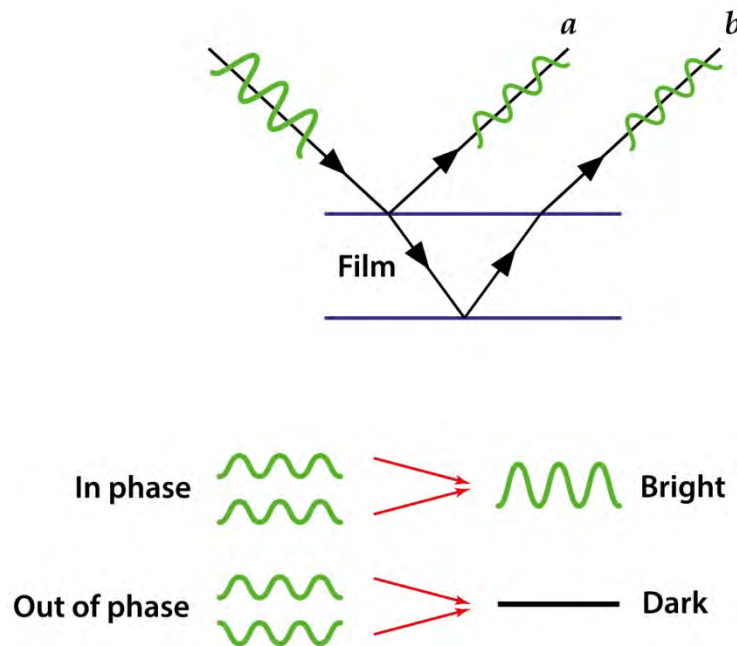


Figure 9: Interference due to temporal coherence.

If the film shown in figure 9 is sufficiently thick and the light has a sufficiently broad bandwidth, the recombining beams *a* and *b* will have originated from different incident wave trains with no fixed phase difference between them. The beams are then said to be temporally incoherent. Interference effects will not occur, as the resultant beam will continually exhibit random changes in amplitude and phase; its intensity will be given by the sum of the intensities of the individual beams.

Between the two extreme cases of temporal coherence and incoherence there is the possibility of the two superposed disturbances being partially coherent *i.e.* there being some overlap of combining waves that have originated from the same incident wave train. In this situation interference effects can occur but will be of lower contrast than when the two beams are completely coherent.

While temporal coherence describes the phase relation in the direction of the light beam, spatial coherence describes the phase relation in a plane perpendicular to the direction of propagation. Thus, in considering the resolution of two point sources by the optical microscope in chapter 2 it was assumed that there was no fixed phase relationship existing between the light waves emanating from these two points. The resultant intensity distribution in the image plane is then determined by the simple addition of each intensity pattern as shown in figure 3.

However, in microscopy, objects are usually illuminated by light from the condenser. Thus, the two point objects should be regarded as two pinholes in an otherwise opaque film. If some of the light passing through each pinhole has originated from the same incident wave train, there will be a degree of spatial coherence between the waves from the pinholes. Now each point in the field stop will be imaged by the condenser as an Airy disc in the object plane, with the diameter of each disc increasing as the condenser numerical aperture is reduced. Thus the coherently illuminated area and hence the degree of spatial coherence in the illumination of two pinholes will increase with decreasing condenser aperture.

Theoretical analysis, taking spatial coherence into account, has shown that the minimum resolvable pinhole separation (based on the intensity criterion used in the section: Image formation and resolution) is given by equation (1) for equal objective and condenser apertures, but with decreasing condenser NA it rises rather more slowly than expected from the Abbe rule (based on the mean of the objective and condenser apertures).

It is therefore evident that an objective of high numerical aperture is essential to achieve maximum resolution. Expressed in a different way, increasing the objective NA results in a higher proportion of light diffracted by the object that is collected by the objective and hence, the greater the similarity between object and image. Although, in theory, the condenser NA should be comparable to the objective aperture to achieve highest resolution, in practice, with a large cone of illumination residual aberrations and multiple reflections in the image forming optics can impair image quality. A satisfactory compromise in terms of image resolution and contrast is often achieved using a condenser NA approximately two-thirds that of the objective.

The degree of spatial coherence of the illumination is a critical factor in the imaging of an opaque edge (as found, for example, in a chromium on glass photomask). Due to diffraction effects the image of a sharp edge is slightly 'blurred', *i.e.* the transition from light to dark is spread over a small distance rather than being absolutely abrupt. This is analogous to a point source being imaged not as a point but as an Airy disc of finite size. Theoretical analysis shows, that with spatially incoherent illumination, the computed intensity profile crosses the true position of an infinitely sharp edge at the 50 per cent level as shown in Figure 10. Edge setting on this 50 per cent intensity level is probably the most obvious one to carry out visually and it is also the most convenient intensity threshold to determine by image analysis techniques.

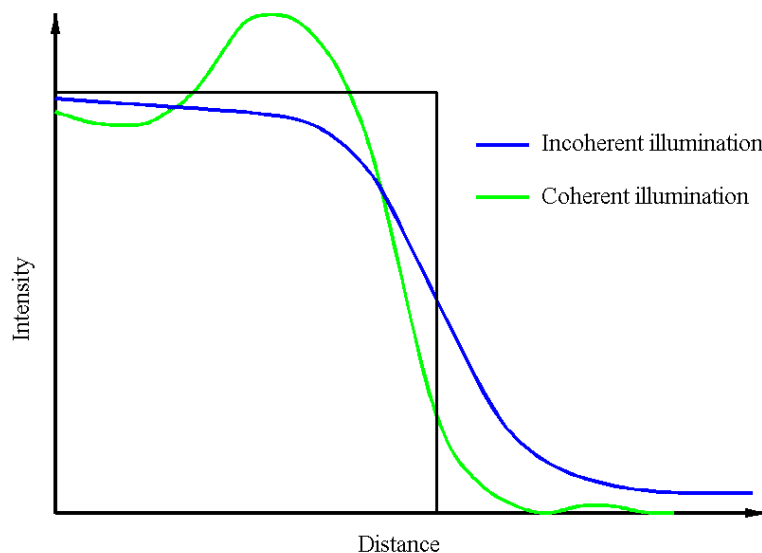


Figure 10: Image intensity profile at a sharp edge.

However, if the illumination is completely coherent across the object plane, the intersection between the true edge position and the image intensity profile occurs at the 25 per cent level (see figure 10) and hence assessment using the 50 per cent criterion will not give the true edge position. This incorrect assessment will occur at both edges of a line and will cause an

opaque line to be measured as wider than its true width and a transparent line as smaller than its true width.

In practice there is usually partial spatial coherence of the specimen illumination in the microscope and the exact image appearance will then be more difficult to interpret. As noted above, by reducing the condenser aperture the degree of coherence is increased and, in fact, for a ratio of condenser to objective numerical apertures of 0.25 or less, the conditions of complete coherence can be considered to apply. Unfortunately, edge diffraction effects, i.e. ringing, are then emphasised, often resulting in an image that appears to possess little direct correspondence to the object.

Optimal microscope use

Figure 11 shows the essential features of a high power optical microscope. The most complex lens is of course the objective and the section of this document on the microscope objective illustrated the properties of various types of objective. A flat field achromat - or better still apochromat - with a magnification of at least $80\times$ and an NA of 0.9 is suitable for high precision dimensional measurement. There are usually several objectives with different magnifications mounted on a rotating turret and if they are a set provided by the microscope manufacturer, they are generally parfocal. This helps to avoid contact between a high power objective and the object after viewing it under low power.

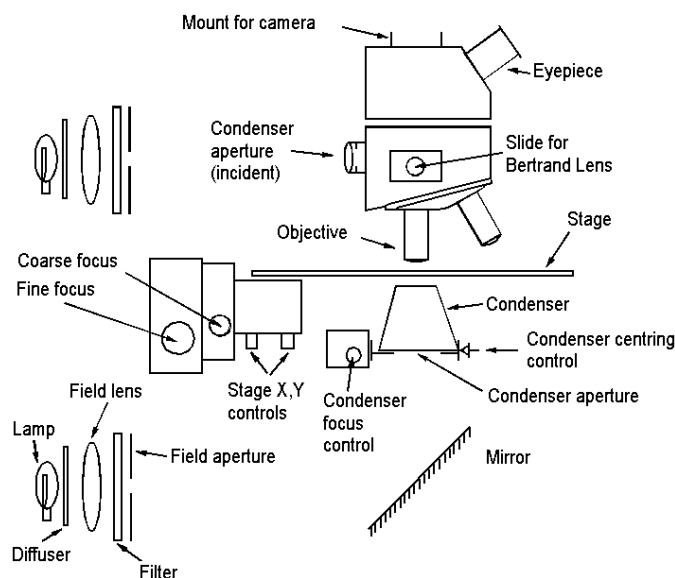


Figure 11: Features of a microscope.

The real image produced by the objective is viewed through the eyepiece or ocular, which may be used singly (monocular) or as a pair (binocular viewing). A binocular head contains provision for altering the separation of the two eyepieces to accommodate varying eye separations of different operators while maintaining a constant tube length. There is also usually a focusing adjustment on one tube. This is provided to enable users, whose eyes require different degrees of correction, to focus clearly on the image. The total magnification of the system is given by the product of the magnification of the objective and the magnifying power of the eyepiece though a complex measuring system and relay lens for tube length correction may affect this figure. The back focal plane of the objective may also be viewed

through the eyepiece if a lens known as the Bertrand lens is introduced into the microscope tube and many microscopes have this facility. The object is mounted on a stage which can be moved in X and Y directions. Its Z motion is achieved by rotation of the coarse and fine focus controls.

The illumination optics should provide uniform illumination of the object field and ensure that the light is collected by the objective. The source is usually a tungsten filament or mercury arc and its light is focused at the object by a condenser lens. If the illumination is incident on and reflected by the object, the objective acts as its own condenser. For objects to be viewed in transmitted light, a separate sub-stage condenser is used and this should have centring adjustments to align it with the axis of the microscope body tube and a focusing control. Both types of condenser have an associated iris diaphragm, called the condenser diaphragm or aperture stop. This is located in the back focal plane of the condenser, either physically so for a sub-stage condenser, or by imaging it with an auxiliary lens in incident illumination. It acts as a control on the effective numerical aperture of the condenser, provided that the condenser iris is filled with light. A field lens ensures that this is so by collecting the light from the source and imaging it at the condenser. This also allows the source to be remote from the microscope, which may be an advantage as far as sample-heating effects are concerned. The field lens has a focus control and an iris diaphragm called the field diaphragm or stop. Other facilities near the source are controls to align it centrally; a removable diffuser located in front of it and racks to hold any filters that may be required.

All the features so far described are found on a basic microscope used for visual observation and inspection. If dimensional measurements are to be made with the microscope, various other features will be present. The simplest measuring tool is a calibrated scale or graticule in the eyepiece. The filar eyepiece provides a crosshair which can be moved from one side of the image to the other by a measurable amount to give an indication of the image dimension and hence that of the object. Most microscopes have a second point of access to the body tube, where a CCD camera may be mounted, to enable the incorporation of an image processing system.

Kohler illumination

Given a light source, which is to be used to illuminate an object on a microscope, perhaps the most obvious way of configuring the illumination system is to use a lens to collect the light and focus the source on the object. This is called critical illumination and is illustrated in figure 12.

If the maximum resolving power of the instrument is to be achieved, it is necessary that the NA of the condenser be nearly equal to that of the object, in practice a value about two thirds of the objective NA is frequently employed, for reasons discussed later. To achieve this cone of illumination the condenser, like the objective, must have a short focal length and be near the object. If the source is remote, very little of its light will be collected by such a condenser. A lamp condenser is therefore required to collect as much light as possible from the source and deliver it to the stage condenser with minimal losses. Auxiliary lenses may also be employed.

The main disadvantage of critical illumination is the fact that non-uniformity in the source intensity distribution is present at the object plane so the object is unevenly illuminated and

this may be particularly severe when using a small source like a tungsten filament lamp. Kohler illumination overcomes these problems and in principle requires only two lenses, though the design of the microscope may make it necessary to include auxiliary lenses, particularly when high and low NA objectives are used on the same turret.

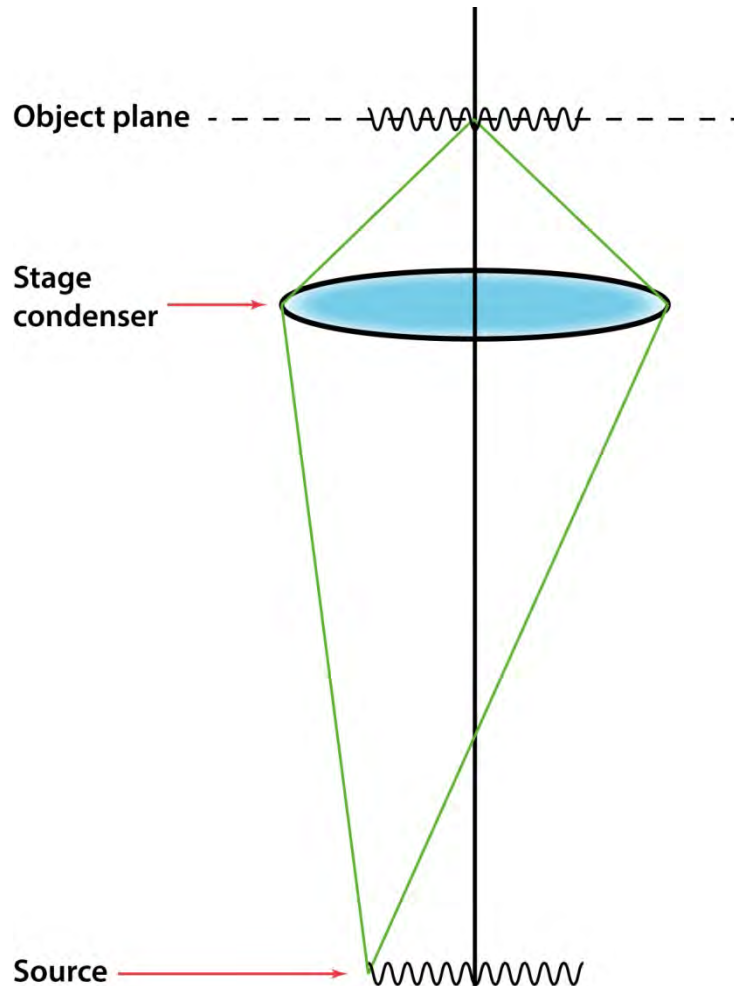


Figure 12: Ray paths for critical illumination.

Figure 13 shows the optical arrangement for Kohler illumination. The source is imaged at the condenser diaphragm by the lamp condenser, which becomes the field lens. This change of name reflects the fact that the stage condenser in the object plane images the diaphragm at this lens. Its size therefore controls the size of the illuminated object field, hence the name of field diaphragm. Now the condenser diaphragm is in the back focal plane of the condenser as noted previously, so each point on the source gives rise to an image point at the condenser diaphragm; this causes a small parallel beam of light to pass through the object field. The illumination of that field is, therefore, made up of a series of parallel beams, inclined relative to each other and originating from different points of the source. These produce a cone of light evenly illuminating the object field. Note that the source and the condenser diaphragm are further imaged in the back focal plane of the objective - the objective pupil - and again at the exit pupil of the eyepiece, where the eye should be placed.

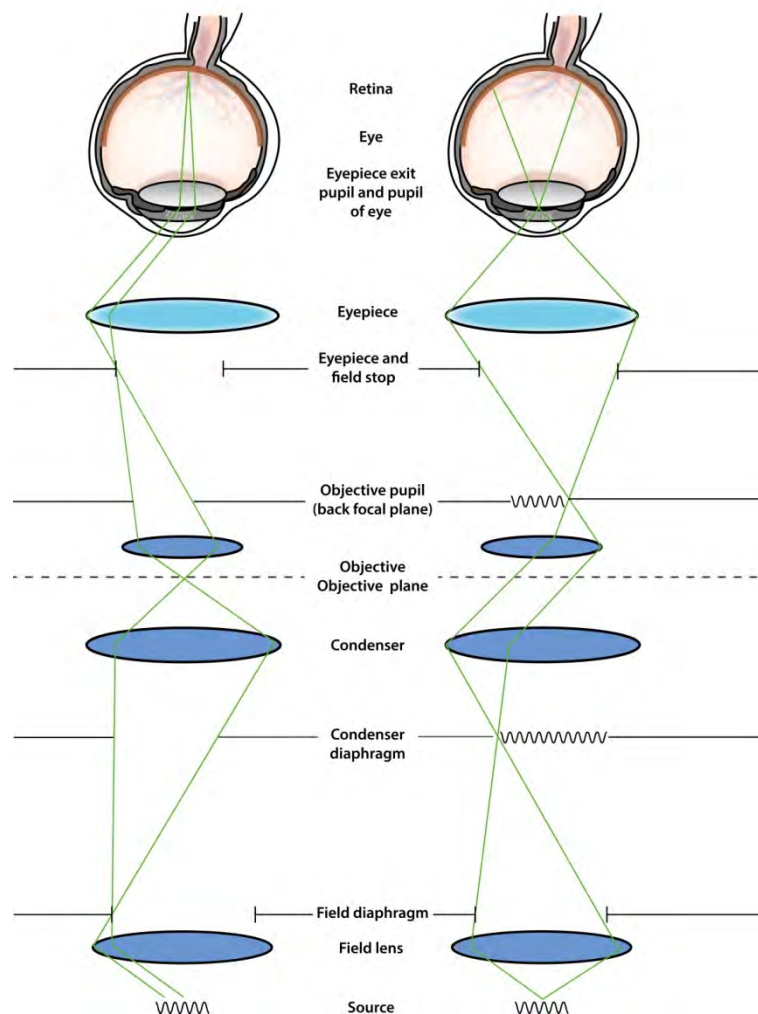


Figure 13: Ray paths for Kohler illumination.

The size of the condenser diaphragm determines the area of the condenser lens actually used and hence the cone angle of the light converging on the object. In other words, the condenser diaphragm controls the numerical aperture of the condenser, so it is sometimes called the aperture stop. As was explained in earlier in chapter 2, reducing the numerical aperture of the illumination increases the spatial coherence so the degree of coherence of the illumination is controlled by the condenser diaphragm. Figure 14 shows the image intensity profiles of an edge - say of a photomask line - in spatially coherent and incoherent light. The image of the coherently illuminated edge is much sharper than achieved with incoherent light, but it does suffer from "ringing" which makes edge detection for measurement rather difficult. Unfortunately, it is impossible to obtain incoherent illumination in high power microscopy. A compromise has to be made between increasing the coherence with the aperture stop closed down and losing contrast through glare and multiple reflections in the microscope lenses with the stop opened up. Experience shows that a condenser NA about two thirds that of the objective gives the best compromise. This does not mean that the full NA of the objective is not used because a typical object scatters light in most directions and the objective will collect some light, not in the main illumination cone.

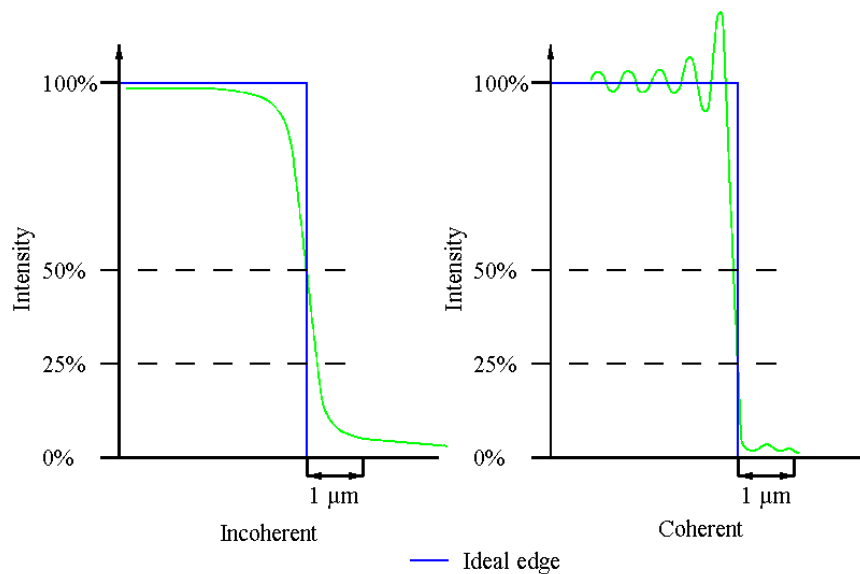


Figure 14: Image intensity profile of an edge in incoherent and coherent light.

Contrast may also be lost if the field diaphragm is open too wide. As it is imaged in the object plane it should, if shut down, be visible through the eyepiece when an object is in focus. It should be opened up until it is just beyond the field of view. Any further opening increases reflection in the body tube and the lenses, all tending to reduce image contrast.

These comments on the diaphragms serve to show that both have certain optimum settings and that neither of them should be used to control the intensity of the illumination. The best way to do that is with neutral density filters, as will be explained later.

Setting up procedure

There now follows a series of instructions with explanatory notes for setting up Kohler illumination in a microscope. It is assumed that all the controls previously mentioned are present. On some microscopes it may not be possible to make all these adjustments, but it is instructive to know how this may restrict the performance of the instrument.

1 - Switch on the microscope

Switching on the microscope, refers to the all the peripheral systems being used, and will ensure that some degree of thermal stability is established when measurement starts.

2 - Put on a pair of lint free gloves

Wearing of gloves is not only a dust precaution. Eyepieces and microscopic optical samples are prone to acquiring fingerprints, which can easily impair image quality.

3 - Remove any obvious dust with clean filtered air

Perhaps this is a superfluous instruction, if clean room conditions prevail, but it is as well to check. A proprietary duster may be used on the illumination optics or the stage plate but not on the object in case a chemical residue is sprayed on the surface.

4 - Ensure that the diffuser is in position

A diffuser will eliminate any residual lamp filament structure in the image.

5 - Move the stage to its lowest and most forward position and place the object on it

Great care is of course necessary to avoid scratches and contact between the objective and the object being examined.

6 - Select the required filter

Use of a filter reduces the chances of any residual chromatic aberration causing image deterioration. As green is midway through the visible spectrum, most objectives are designed to perform well in green light. A green filter with a bandwidth of about 100 nm, such as the OGR1 or the VG9, is therefore suitable for use with a tungsten filament lamp as source. Neutral density filters may also be required to control the illumination intensity.

7 - Open the field and condenser diaphragms

Opening the diaphragms is just to ensure that enough light is transmitted by the unadjusted system to make the object visible.

8 - Select the lowest power objective and focus on the object

It is inadvisable to grasp the objectives when rotating the turret as they may be screwed into adjustable, sprung mounts for alignment purposes and can become misaligned if pulled; always grip the turret itself. Move the stage to locate the relevant area of the object under the objective, and then move it towards the objective with the coarse focus control until it is slightly closer than the working distance and then obtain a sharp image using the fine focus control. This procedure minimises the risk of contact between the objective and object. Find the region of interest and select the required objective.

If the objectives are not a parfocal set, the stage should be lowered and the image refocused when changing from low to high power.

With a graticule or filar eyepiece, ensure that the lines in its field of view are sharp when the eyes are relaxed. Remove the eyepiece and look through it with one eye while viewing a distant object with the other. The eyepiece focusing can then be adjusted to make the lines in the field of view appear sharp.

With a binocular eyepiece, ensure that the image is sharp for both eyes and that the distance between the eyepieces is correct. Firstly, cover the eye looking down the adjustable eyepiece and focus the microscope for the other eye using the stage fine focus control. Then cover the other eye and obtain a sharp image with the eyepiece focus control.

9 - Close the field diaphragm and focus it in the field of view using the condenser focusing control

Due to the imperfect correction of the condenser and further aberration introduced by subsequent mounting plates, the image of the field diaphragm tends to be rather poor in transmitted illumination.

10 - Centre the diaphragm image in the field of view, using the controls on the condenser

11 - Open out the field diaphragm to just cover the field of view with uniform illumination

As mentioned before, opening it any further will introduce stray reflections that reduce contrast.

12 - Remove the diffuser, then centre and focus the image of the lamp filament in the plane of the condenser diaphragm. Use the source centring and field lens focus controls for this. Strictly, it should be the diffuser that is focused in this plane but it is easier to see the image of the filament.

13 - Close the condenser diaphragm down and focus the filament image on it or on a piece of paper held against it. If this diaphragm is not accessible remove an eyepiece or insert the Bertrand lens and adjust the focus of the filament image until there is no parallax between it and the objective pupil.

14 - Replace the diffuser and adjust the condenser diaphragm to be $\frac{2}{3}$ the diameter of the objective pupil, as shown in figure 15.

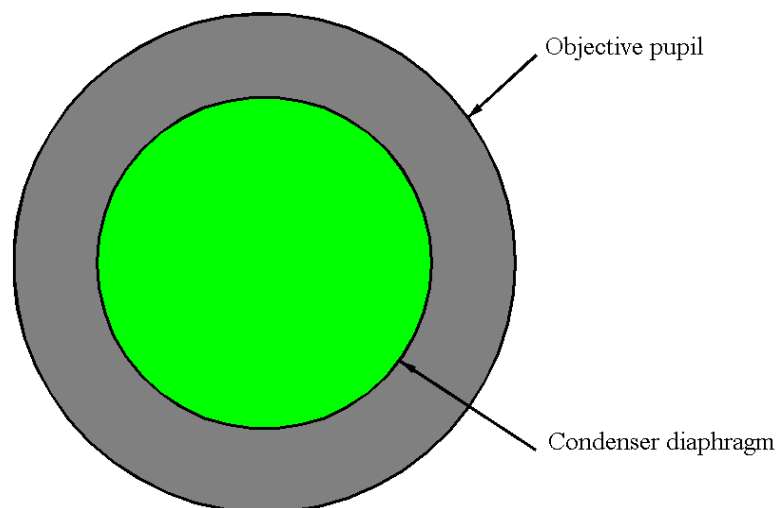


Figure 15: Condenser diaphragm set at $\frac{2}{3}$ diameter of the objective pupil.

If the condenser is calibrated in NA the diaphragm need merely be adjusted to the appropriate mark. If not, the pupil must be observed directly down the tube either by removing an eyepiece or through the eyepiece via the Bertrand lens. Calibrating the condenser in terms of NA saves time in subsequent setting up of Kohler illumination. This is easily done by making a few measurements on the cone of light produced by the condenser as its aperture is varied. It is helpful to know what a circle $\frac{2}{3}$ the diameter of another looks like beforehand - see

figure 15. With high NA objectives, the limiting aperture is that of the condenser as the periphery of the objective pupil is difficult to see. A piece of lens tissue placed between the objective and the object may scatter enough light to make the pupil visible.

Imaging microscopic features on large samples

The size of sample that can be measured is also dependent on the stage size and objective working distance. A microscope is likely to have a maximum stage size of 150 mm x 150 mm and a maximum working distance of 10 mm - 15 mm. If the sample is larger than this, different methods of illumination and imaging are required.

The ability to measure microscopic features on a large sample can be achieved by using a programmable power turret. Two methods are used for switching the magnification in this type of optical system. One method switches the objective lens (the one nearest the workpiece) and the other method changes the zoom ratio of the imaging lens (optical tube). There are limitations to both methods. Switching the objective lens may disturb dust over the workpiece surface and its structure does not allow ring illumination to be used at the same time. In the second method, magnification switching using only a zoom lens can result in poor repeatability, or the image position may deviate (called image jump) after the switch.

To overcome these limitations, a system can be used that incorporates objective lenses in three optical tubes within the objective turret, see figure 16. These optical tubes, with different focal lengths can be switched by turret revolution. This results in three stages of optical magnification 1×, 2× and 6× to cover a wide field of view and high magnification. The objective lens uses a standard 2.5× specification. In addition, a 1× objective and a 5× objective are available which provides nine choices of magnification between 32× and 960×, as shown in table 4. This allows the system to deal with a wide range of measurements, from wide area measurement to partially enlarged measurement.

Table 4 total magnification of objective and optical tube combinations

		Objective			Magnification by monitor	Overall magnification		
		1×	2.5×	5×				
Optical tube	1×	1×	2.5×	5×	32×	32×	80×	160×
	2×	2×	5×	10×		64×	160×	320×
	6×	6×	15×	30×		192×	192×	960×

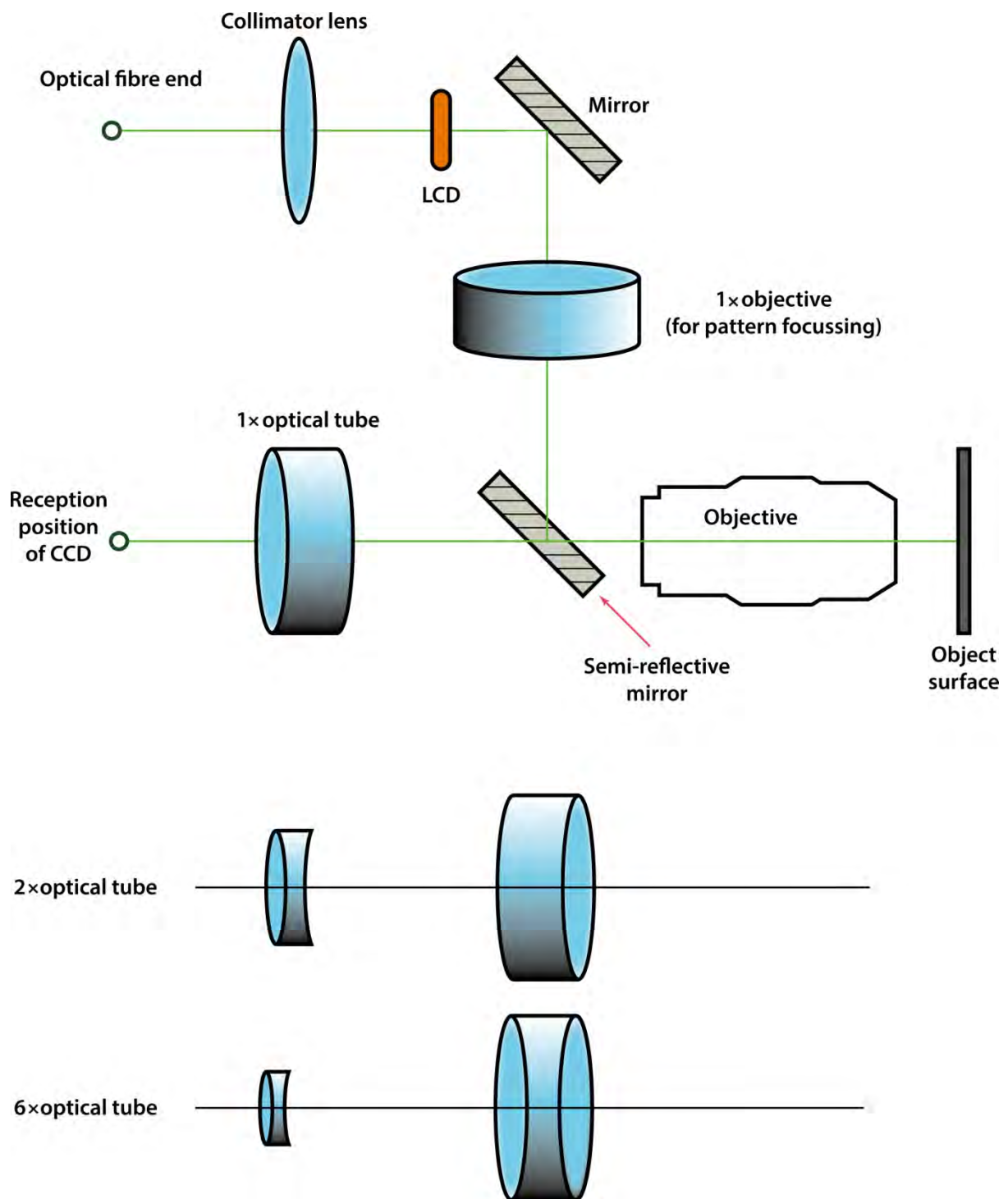


Figure 16: Schematic of a programmable power turret system.

Chapter summary

- Be aware of resolution and how images are formed.
- Be aware of the types of aberration in the image forming system.
- Be aware of the optical components of a microscope.

- Be aware of coherence.
- Know how to use a microscope.
- Be aware of factors influencing imaging large samples.

Macroscopy

3

IN THIS CHAPTER

- Illumination sources for macro vision systems
- Illumination configurations
- Chapter summary

Vision systems designed for measuring macroscopic objects are likely to use an optical arrangement that will give a larger field of view with increased depth of focus. Such a system is unlikely to have its illumination system and imaging optics integral and hence, care must be taken to employ the most suitable components to achieve a good image. Figure 17 shows the basic features of a macro vision system used in a production environment.

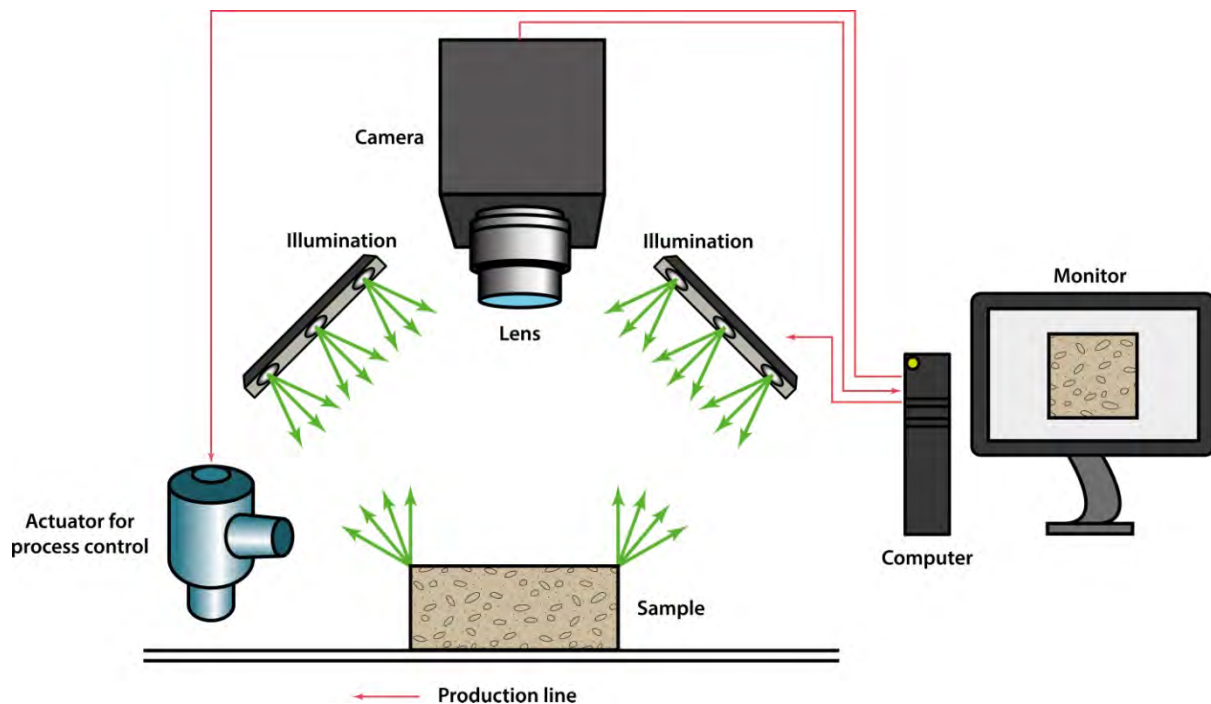


Figure 17: Macro image processing system.

Illumination sources for macro vision systems

Whilst there are many different lighting configurations available, there are only a small number of illumination sources in common use.

Halogen lamps

Halogen lamps can be configured as low cost and flexible cold light sources. The lamp assembly is however normally hot and therefore should be placed away from the measurement system. Halogen lamps are frequently used with fibre optic light guides, where directional illumination is required. As the lamps use a Direct Current (DC) power supply, brightness variation due to mains frequency is avoided. They are ideally suited for high accuracy dimensional measurement, especially if a regulated power supply is used.

Xenon strobe lamps

These lamps are most associated with high speed imaging, perhaps on a high volume production lines. They are long life lamps, producing high intensity, daylight colour temperature illumination. They can be used with fibre optic light guides and the more expensive types can be synchronised with the camera shutter. Xenon arc lamps are also available, providing a constant high intensity output, but there are few applications requiring this type of illumination.

Fluorescent tubes

Fluorescent tubes are the most common source of illumination for macro vision systems. They give a very bright, homogenous illumination, but do show periodic intensity variations, as they are normally powered by an AC supply. The use of high frequency fluorescent tubes with long persistence phosphors can reduce this intensity variation. Fluorescent tubes are ideally used as large area backlights and for front flood lighting. They are also commonly used in line scan applications.

LED lighting

Perhaps the most versatile illumination source, Light Emitting Diodes (LEDs) are very reliable and can be switched, strobed or operated continuously. The illumination intensity can equal or exceed that of halogen lamps. White light and monochromatic LED's are available and the configurations include ring lights, rod lights, line lights, backlights and on-axis diffuse lighting. Modern LED's are generally energy efficient but can be more expensive than other sources.

Lasers

Whilst not generally used for dimensional measurement, laser sources offer a low power, monochromatic and high reliability illumination. They are particularly suited to structured illumination requirements, where high intensity grids, lines, spots or concentric circles can be created with additional optics. A typical gauging application would be dimensional measurement using laser line illumination on parts with little grey level contrast.

Illumination configurations

As with microscopy, large area vision systems use transmitted or reflected illumination, although on the macro scale they are known as back lighting or front lighting, respectively. The following sections describe the most common illumination configurations.

Diffuse front lighting

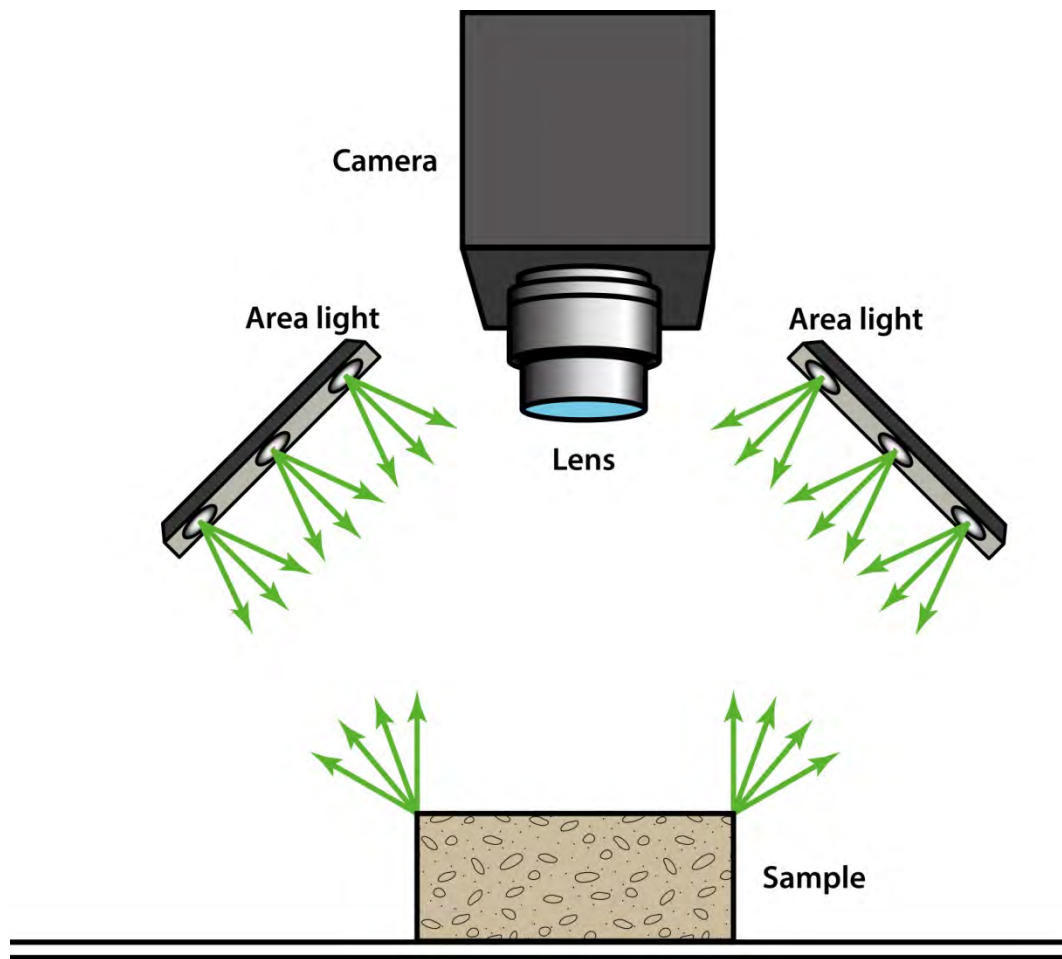


Figure 18: Diffuse front lighting.

The light provided by this type of illumination has no directionality and thus minimises specular reflections and shadows. Illumination is achieved by mounting the source behind a large area diffuser, or by reflection off a white screen, as shown in figure 18.

Directional front lighting

Also known as dark field illumination, directional front lighting is designed, so that reflections from smooth surfaces do not enter the camera lens. Surface features, such as indentations will appear to have bright edges as their reflectance angles are different, creating a large contrast with the surface, as shown in figure 19. Certain gauging applications may require the incident light to be almost parallel to the surface, using a line light. This will create high contrast on textured surfaces and is called oblique lighting.

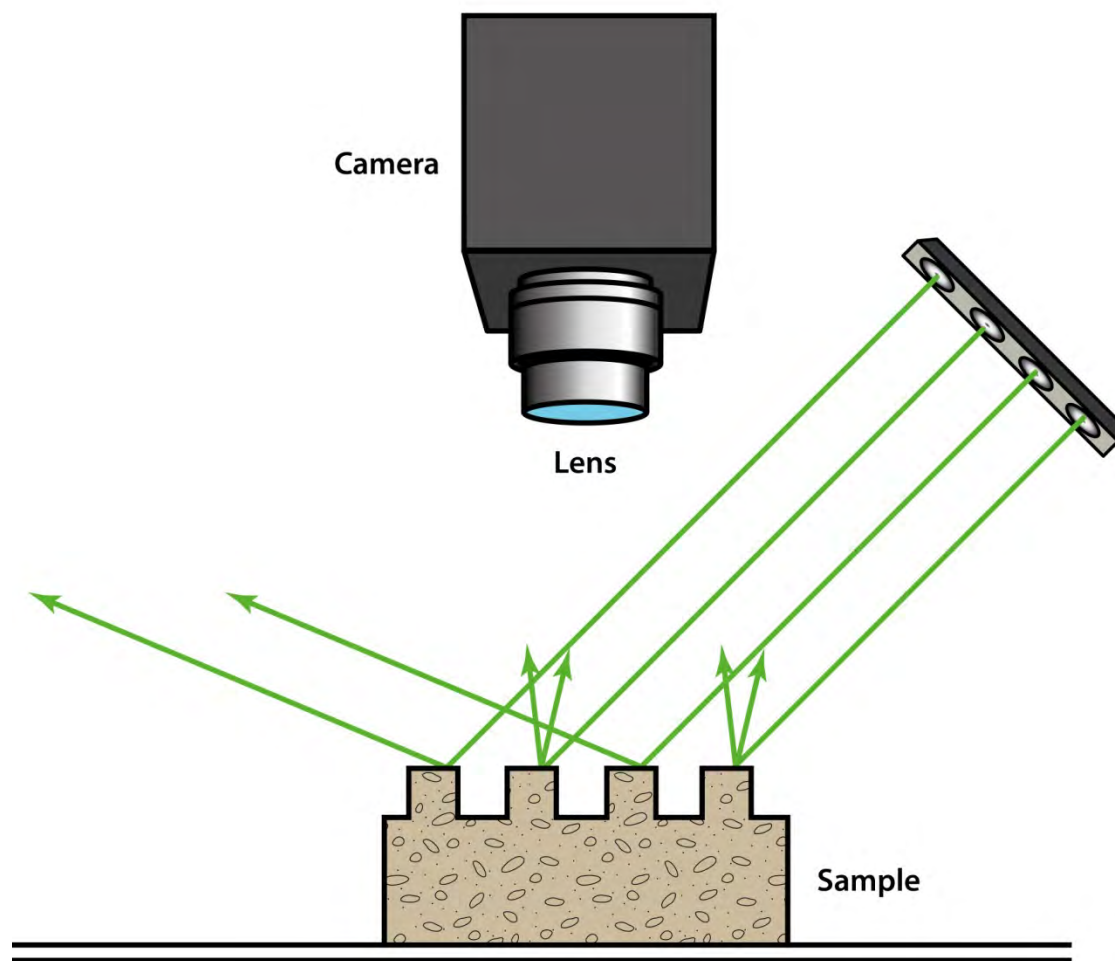


Figure 19: Directional front lighting.

Ring lighting

Ring lighting, as shown in figure 20, is available in different configurations, using many of the illumination sources described previously. This provides shadow free illumination along the optical axis of the camera and is especially useful when imaging objects with high reflectance. Some workpiece parts, subject to dimensional measurement, may not have a sharp edge convenient for edge detection but a curved or chamfered edge. In these cases, simple reflected illumination will not result in high accuracy edge detection since it produces an image contrast with a gradual intensity curve. In extreme cases, no form of edge detection may be attainable. Using ring light illumination makes it possible to enhance the image contrast and perform highly reliable edge detection.

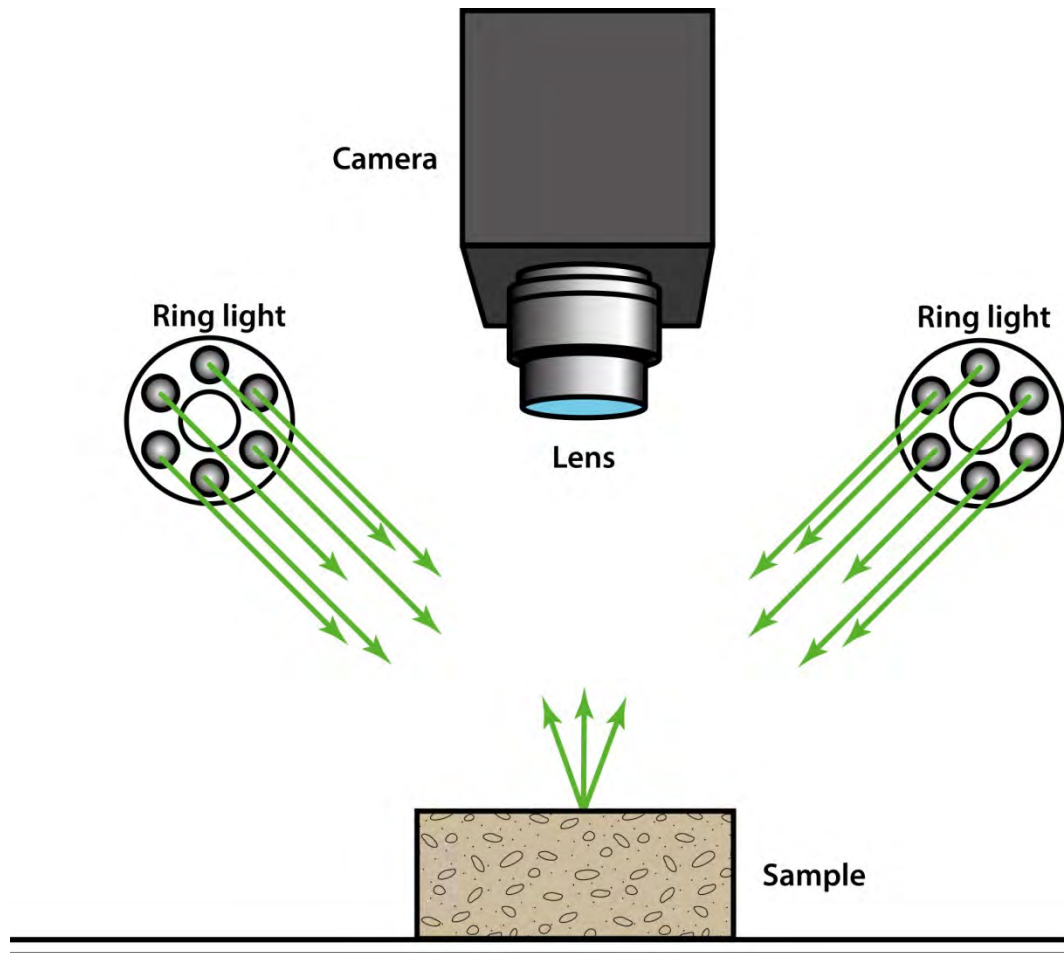


Figure 20: Ring light illumination.

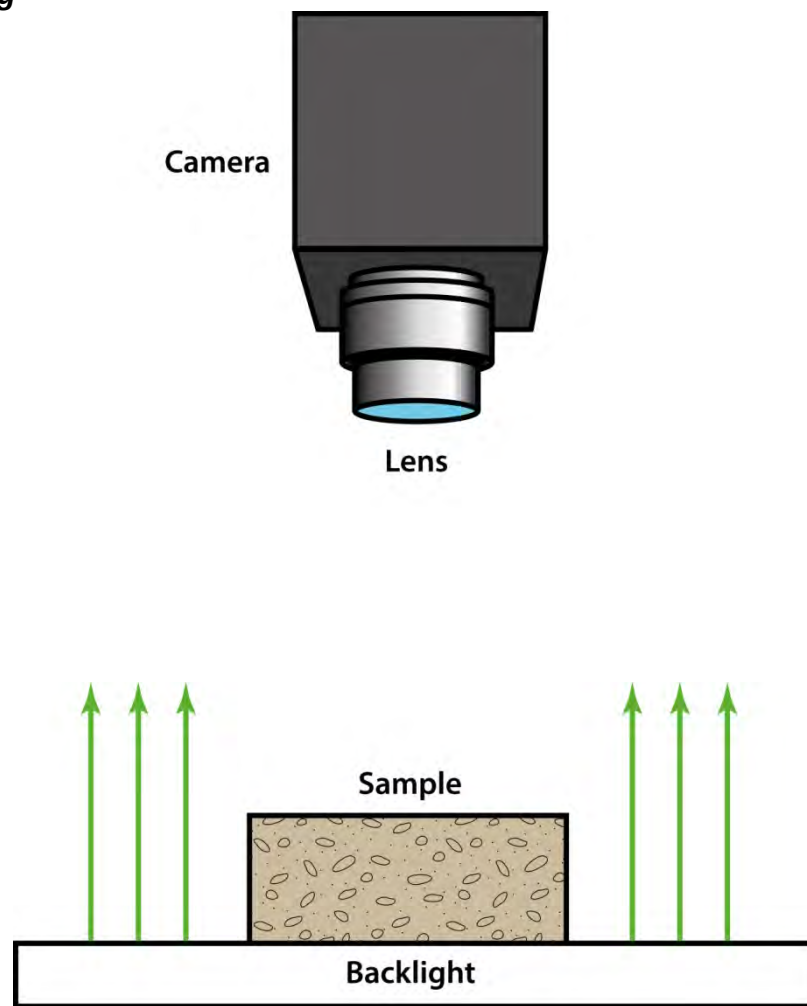
Back lighting

Figure 21: Back light illumination

Back lighting, as shown in figure 21, involves the sample being between the camera system and a flat field light source. This arrangement generally gives excellent contrast at the edge of the sample but is of course no use for seeing features within the sample unless the sample itself is transparent with opaque features (for example a chrome on glass scale).

Selection of appropriate lighting configurations

Some systems may have different illumination configurations available to the operator. Different jobs require different illumination arrangements and the selection is largely down to trial and error and operator experience. Manufacturer's guidance where available will also be useful. It is always good practice to record the illumination setup and lighting level used for a measurement job, so that measurements can be repeated in future.

Care should be taken since different illumination patterns may give different results for the same target. A simple example is the measurement of the diameter of both ends of a drilled hole through block of opaque material to check for taper. The hole is measured on one side then the block is turned over to measure the other end of the cylinder. If back lighting is used the diameter at both ends of the hole will appear the same size while measurements made using front lighting will show them to be different. The two lighting configurations give different answers for the same measurement.

The reason for this difference is that the backlighting will only show the smallest diameter between the light source and the camera (this can be very useful in some cases) while the front lighting shows the nearest diameter to the camera, be that big or small. So although it appears that the same measurement has been made, in fact the two lighting configurations are measuring two different things.

This example illustrates the need for care with illumination choice due to the risk of errors caused by different illumination. Care must be taken to ensure that the illumination choice made is suitable and allows measurement of the correct features.

Chapter summary

- Be aware of the different illuminations sources.
- Be aware of the different illumination configurations.
- Take care in the selection of lighting configurations.

Lens configurations for macroscopic systems

4

IN THIS CHAPTER

- Optical principles
- Modulation transfer function
- Aberrations in the image forming system
- Lens selection
- Commercial lenses

There are several different types of lens suitable for use with vision systems. Typically, they will all have 'C' or 'CS' mount fittings to enable connection to a CCD camera. Before describing the attributes of the different kinds of lens, it is first worth considering the various factors that affect how an image is formed on the camera.

Optical principles

In order to appreciate the factors that affect how an image is formed on the camera it is necessary to go back to first principles and look at the basic formulae and associated definitions that describe the operation of a simple lens.

The *f*-number

The aperture setting of a lens controls the amount of light passing through it. Figure 22 shows a lens of focal length, f with a diaphragm that sets the effective lens aperture to diameter, d . The term 'relative aperture' is defined as the ratio of the lens diameter to its focal length (d/f).

A more commonly used term describing the lens aperture is the *f*-number or *f*-stop. This number is defined as the reciprocal of the relative aperture

$$N = f/\# = \frac{f}{d}. \quad (5)$$

The light collecting power of a lens is proportional to the square of its relative aperture and hence is inversely proportional to the square of the *f*-number. The light collecting power therefore decreases by a quarter as the *f*-number doubles. Camera lenses are often classified in terms of their minimum possible *f*-number, the smaller the *f*-number the more sensitive, or higher speed, is the lens.

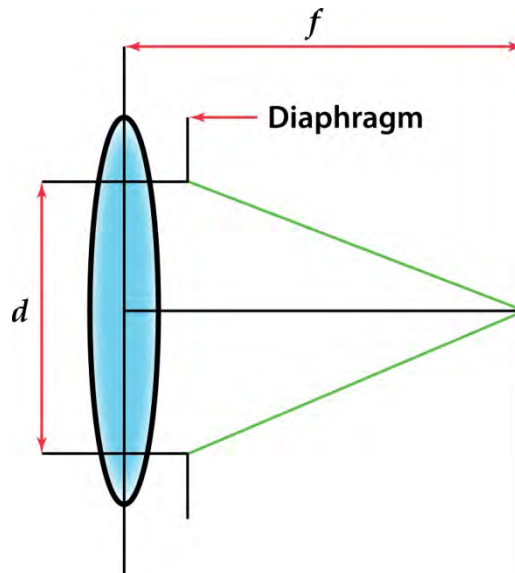


Figure 22: Lens relative aperture.

Thin lens formulae

Equations 6 to 10 are based on the assumption that the dimensions of the lens, do not affect the formation of an image. Figure 23 shows the image formed by a thin lens. In this case the lens is actually producing an image that is smaller than the object.

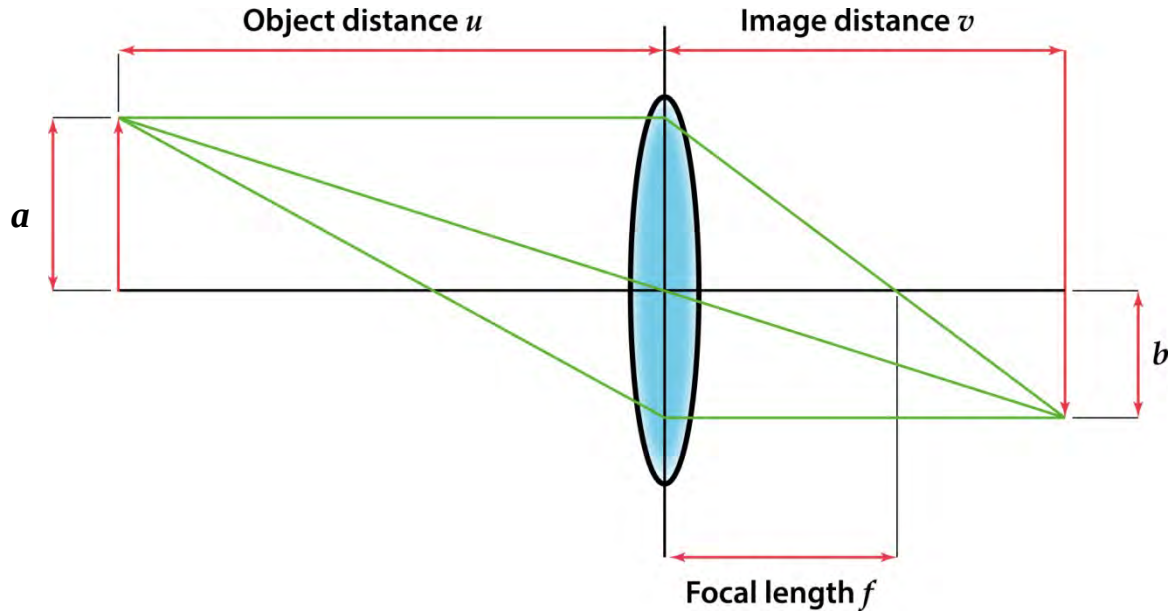


Figure 23: Image formation by a thin lens.

The lens magnification (M) is given by the ratio of the image height (b) to object height (a). It can be seen from figure 22 that the magnification can also be expressed as the ratio of the image distance (v) to object distance (u):

$$M = \frac{b}{a} \text{ and } M = \frac{v}{u}. \quad (6)$$

The thin lens imaging equation is:

$$\frac{1}{f} = \frac{1}{u} + \frac{1}{v}, \quad (7)$$

where f = focal length.

By rearranging equation (7) the image distance v , can be expressed in terms of the object distance u and the focal length f :

$$v = \frac{uf}{(u - f)} \quad (8)$$

If equations (6) and (8) are combined the image size can be expressed in terms of the object size, focal length and object distance as follows:

$$b = \frac{af}{(u - f)}. \quad (9)$$

Two optical properties of this simple imaging system may be deduced from equations 8 and 9. Firstly, for a given object size and distance, increasing the focal length increases the size of

the image. Secondly, for a given object size and focal length, moving the lens closer to the object increases the size of the image. In both cases the image distance also increases.

Hence in a vision system, employing a camera at the image plane, changing to a longer focal length lens, or moving the lens closer to the object to increase the magnification will also require that the lens is moved further away from the camera in order to keep the image in focus. In practice, this is normally achieved by simply rotating the lens tube.

Two of the most important criteria when selecting the correct lens for a vision system, are the field of view and the angle of view. The size of the object to be measured is a key factor, as the whole object must fall within the field of view in order that it may be measured. Rearranging equation (9) gives an expression that can be used to calculate the maximum object size (a) that can be seen by the camera:

$$a = \frac{b(u - f)}{f} \quad (10)$$

Where; b = image height, determined by the size of the CCD sensor

The angle of view is important as it defines the physical position of the lens and camera. The angle of view β can be expressed as:

$$\beta = 2\tan^{-1}(b/2f). \quad (11)$$

Depth of field

Equation (7) indicates the relationship between the focal length and the object and image distances for a single thin lens where it is assumed that the lens dimensions do not affect the formation of the image. In this case there is only one image distance at which an object will appear in focus for a given object distance and focal length. In reality, the lens dimensions do affect the image and a typical camera lens will consist of several lenses. With such lens assemblies, there will be a range of object distances at which there will be no discernable defocusing of the image.

As we are imaging on to a CCD camera, we may consider the object's depth to be a series of points, with any given point, half the size of one pixel. Selecting the point size as half a pixel means that it cannot illuminate two pixels at the same time. The point is out of focus if it does not appear as a point (*i.e.*, it is imaged as greater in size than 1 pixel). On the image plane, it is imaged as a circle of confusion. In figure 23, P1 indicates the image distance of point 1 on the object and P2, the image distance of a point 2 on the object. The distance P2 - P1 indicates the depth of field and 'C' is the diameter of the circle of confusion created by point 2 on the image plane of point 1. Despite divergence of the border rays of point 2, if the circle of confusion is less than one pixel, the point will remain sharp in the image.

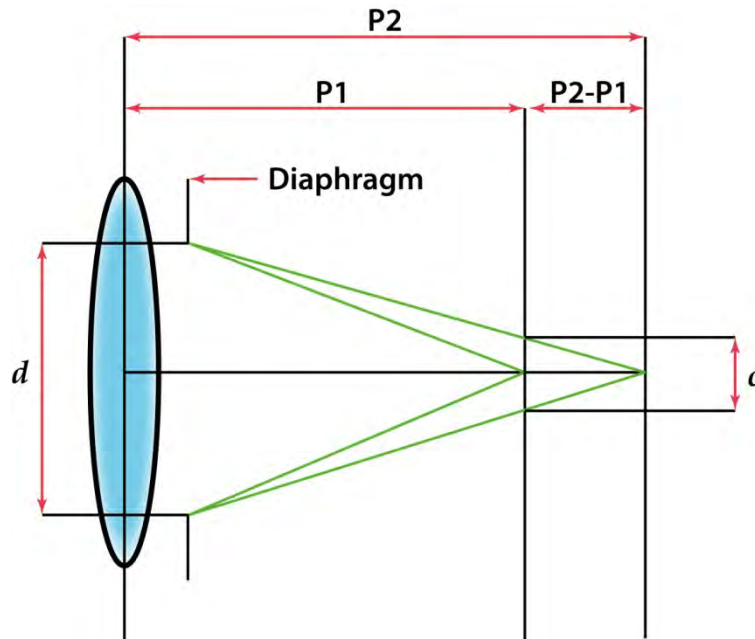


Figure 24: Circle of confusion.

From Figure 24, it can be seen that there are several factors determining whether points on an object are imaged in focus. These are:

- the image distance of point 1 of the object;
- the image distance of point 2 of the object;
- the size of the aperture of the lens; and
- the diameter of the circle of confusion.

The following two equations give an approximate value for the depth of field and the hyperfocal distance. The hyperfocal distance, h , is that distance where objects beyond it will always be in focus in the focal plane:

$$h = \frac{f^2}{ck}, \quad (12)$$

and to calculate the depth of field of object distances less than h , the following approximation applies:

$$d = u/1 \pm (ck(u - f))f^2, \quad (13)$$

where

- d = depth of field;
- u = object distance;
- c = diameter of the circle of confusion;
- k = f -number; and
- f = focal length.

The $\pm$ sign indicates the upper and lower values for the depth of field.

The following tables show the effects on the depth of field caused by changing the image distance (focal length), the size of the aperture of the lens (f -number) and the object distance.

Table 5 Depth of field with varying focal length.

Focal length /mm	d min /mm	d max /mm	Depth of field /mm
1	30.01	∞	∞
2	68.83	467.65	398.82
4	101.46	146.82	45.36
8	114.93	125.54	10.60
16	118.78	121.24	2.46
32	119.74	120.26	0.52
64	119.96	120.04	0.08

f -number = 5.6

Object distance = 120 mm

Circle of confusion value = 0.0045 mm

Table 6 Depth of field with varying f -number.

f -number	d min /mm	d max /mm	Depth of field /mm
1	119.60	120.41	0.81
1.4	119.44	120.57	1.13
2	119.20	120.82	1.62
2.8	118.88	121.14	2.27
4	118.40	121.64	3.24
5.6	117.77	122.31	4.54
8	116.85	123.33	6.48
11	115.70	124.63	8.92
16	113.85	126.85	13.00
22	111.71	129.62	17.92
32	108.30	134.53	26.23

Focal length = 12 mm

Object distance = 120 mm

Circle of confusion value = 0.004 5

Table 7 Depth of field with varying object distance.

Object distance /mm	d min /mm	d max /mm	Depth of field /mm
100	99.18	100.83	1.65
200	196.44	203.69	7.25
400	385.43	415.71	30.28
800	742.68	866.90	124.22
1600	1384.17	1895.57	511.39
3200	2436.38	4660.82	2224.44
6400	3930.18	17223.98	13293.80

f -number = 5.6

Focal length = 16 mm

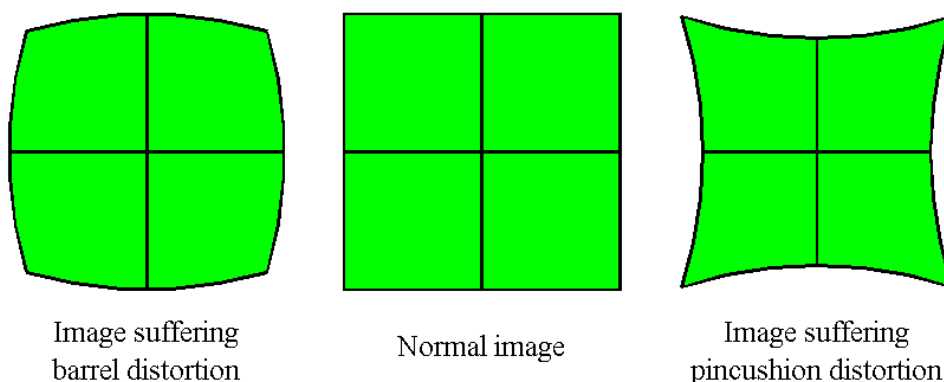
Circle of confusion value = 0.004 5 mm

Modulation transfer function

The resolution of a lens is often described in terms of its modulation transfer function (MTF), which is expressed in line pairs per millimetre. It is a measure of the ability of the lens to transfer contrast information from the object to the image plane, *i.e.* the CCD sensor. A typical standard resolution lens would have a modulation transfer function of 50-100 lines per millimetre at the centre of the lens, which corresponds to a resolution of 10 μm to 20 μm . It is apparent, therefore, that for high accuracy dimensional measurement, only high quality lenses should be used.

Aberrations in the image forming system

A full description of the types of aberrations that occur in lenses is given in chapter 2. Lenses used in macro vision systems are particularly susceptible to distortions due to the large size of the imaging optics. This causes different magnifications for different imaging angles across the aperture of the lens. This type of distortion, known as barrel or pincushion distortion, is shown in figure 25, with the distortion greatly exaggerated in order to clearly illustrate the effect. Distortion values of 1 % to 3 % on the edges of standard lenses are not uncommon.

**Figure 25: Image distortion.**

Lens selection and mounts

As mentioned previously there are two standard types of lens mounts for lenses and CCD cameras, namely C and CS mounts. It is worth noting that the mounts have different flange back lengths, that is, the minimum distance between the lens and the sensor. In the C mount this distance is approximately 17.5 mm and in the CS mount, it is approximately 12.5 mm. From this, it can be seen that a CS lens cannot be used with a C mount camera, as the lens cannot be positioned close enough to the camera. However, C lenses may be used with CS mount cameras if a 5 mm extension ring is used.

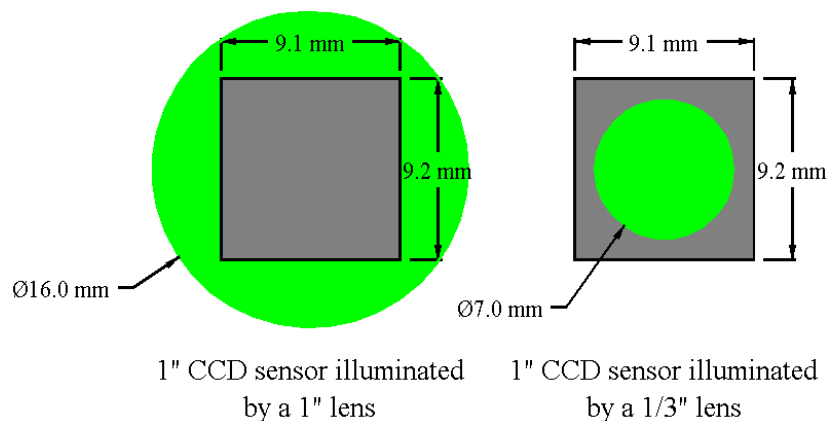


Figure 26: Selecting the correct lens/CCD sensor format.

Lenses and cameras are supplied in a standard formats. The lenses and CCD arrays are described in imperial sizes as 1", 2/3", 1/2" or 1/3". These sizes do not actually correspond to the actual sensor size on the CCD camera but are there to match the camera to the correct lens format. Figure 26 shows how the format describes the lens/camera association. It can be seen that by using unmatched cameras and lenses, the sensor area may not be fully illuminated.

Commercial lenses

Standard lenses

These lenses are designed for low-resolution vision system applications and are generally supplied in 1/2" or 2/3" format. The minimum object distance is typically 200 mm or more. Distortion at the lens edges may be as much as 3 %, with a MTF of 30 lines per mm in that region. Their use should be limited to presence verification applications only.

High resolution lenses

Made with precision-coated optics, these lenses are suitable for use with small pixel CCD cameras. Distortion values are typically less than 1 % and resolutions in excess of 125 lines per mm are available. Various lenses are available with minimum object distances from 1 mm to 1200 mm, in the 1/2" or 2/3" format.

Macro lenses

Vision systems use Macro lenses where small fields of view are required. Image distortion is generally less than 0.1 %, with resolution as high as 200 lines per mm. On-axis illumination fittings are common and magnification up to 12× is available.

Telecentric lenses

This is, perhaps, the most widely used vision system lens for dimensional measurement. It is different to other lenses in that, within a particular range, known as the telecentric range, variations in the height of features on an object do not cause a change in the image size. Therefore, the image does not suffer perspective distortions. In addition, image distortions are low, in the range of 0.1 % to 0.9 %. The lens also has constant magnification and a large depth of field within the telecentric range. The drawback to the use of telecentric lenses is that the object size cannot be greater than the diameter of the lens.

Chapter summary

- Have a good understanding of optical principles.
- Be aware of aberrations in the image forming system.
- Take care with lens selection, noting the difference between C and CS Mounts.
- Be aware of the available commercial lenses.

Cameras

5

IN THIS CHAPTER

- Linearity
- Data transmission
- Analogue Cameras
- Digital cameras
- Linescan cameras
- Chapter summary

A CCD is the most common type of camera sensor used with vision systems. Instead of using film, a CCD sensor positioned behind the lens converts light intensity into electronic signals that can then be transmitted directly to a computer. The sensor consists of a discrete number of light sensitive points, called pixels, formed in a 2D grid. Advances in manufacturing technology have reduced the size of microchips and therefore CCD cameras are becoming increasingly smaller and faster. This has also led to the development of high-resolution cameras with active areas containing more than 1,000,000 pixels. These types of cameras can be employed to cover large fields of view, whilst still achieving high accuracy.

The CCD active area is normally sensitive to wavelengths of light from around 400 nm to 1000 nm (visible to infrared wavelengths). Modern cameras can discern between 256 and 16 384 graduations (8 to 14 bits per pixel). For dimensional measurement using edge detection 8-bit cameras are normally more than adequate. Most modern CCD cameras are capable of outputting the pixel clock, providing synchronisation between it and the frame grabber. They usually also provide other features such as Automatic Gain Control (AGC)*, which adjusts the sensitivity of the CCD sensors to match the image brightness and an electronic shutter, which allows selection of the exposure time of the CCD array.

**Note: AGC should never be used when performing dimensional measurement as it may cause variations in the image intensity levels.*

Linearity of sensitivity response

When choosing a camera it is worth investigating the linearity of its sensitivity response. This is particularly important if the application involves imaging over a wide brightness range. In such cases it is advisable to check the linearity of the camera's response with neutral density filters or a calibrated step wedge.

Data transmission

Analogue CCD cameras use the American RS-170, or the European CCIR video standards. The cameras output a voltage signal that corresponds to the brightness level of individual pixels. Both standards use 0-700 mV for the output signal, 0 mV being black and 700 mV white. The full frame transmission rates are slightly different, with RS-170 at 30 frames per second and CCIR at 25 frames per second.

Digital cameras, by their discrete nature, require their own separate video standards, RS-422 and RS-644, which is the LVDS (Low Voltage Differential Signalling) format of RS-422. They offer data transmission rates of up to 400 MB per second. The main drawback to these standards is the requirement for bulky and inflexible cables for the data transmission. Added to this is a lack of inter-changeability between cameras and frame grabbers, which often results in very expensive, bespoke cabling solutions.

The Camera Link cable specification is a standard specifically designed for the scientific products. It includes data transmission, camera control and asynchronous serial communication, all on one cable. The basic standard has a maximum data rate of 2.3 GB per second. More recently Camera Link 2.0 introduced the HS standard which increased the bandwidth to 48 GB per second. Camera Link is found in most purpose built visions and is

the standard of choice for high performance vision systems generally. It is not generally found outside of scientific applications therefore specialist hardware is required such as interface cards.

Many modern stand-alone cameras are fitted with USB connections (mainly USB 2.0 but increasingly USB 3.0 is being adopted). The standardised nature of USB means that cameras can interact with computers and other instruments with minimal trouble although it does require a bus master, typically a PC. Data transfer rates over USB 2.0 are up to 35 MB/s. USB 3.0 rates are up to 500 MB/s.

IEEE 1394 connections, commonly known as FireWire, can sometimes be found in optical systems, particularly in frame grabbers. Although it is slightly slower than USB 3.0 it has the advantage of being a peer-to-peer connection meaning that a bus master is not required. FireWire is now largely obsolete but may still be present in older systems.

Some systems may also use wireless connections or Ethernet ('Gig E') connections. These provide some flexibility of setup, allowing remote operation, but with increased risks relating to signal loss.

Analogue cameras for vision systems

Interlaced (or synchronous) cameras

Analogue CCD cameras operate using either RS-170 or the CCIR video standards. The output signal requires digitising by a frame grabber, the operation of which is described in chapter 6. The scan mode of this type of camera is interlaced. This means that to build a complete image the camera has to make two exposures, odd lines first, then even. The separation of these images is 20 ms, so this type of camera is not suitable for high-speed imaging. The effect of this is called the field offset. The video output is constant or synchronous, at 25 frames per second. The transmission time of a new image can be up to 80 ms after the request from the vision system.

Progressive scan cameras

This type of camera allows the image to be built up sequentially, row by row. As only one exposure is required, transmission of the image is in its entirety, which makes progressive scan cameras ideally suited to high-speed applications. Processing of the image is also faster than with interlaced scans, since there are no delays caused by having to re-assemble the image.

Asynchronous cameras

An asynchronous camera is able to capture an image on demand from the vision system. This allows faster image transmission (40 ms) than standard cameras, as the camera does not have to wait for the end of the current image before capturing the new image. This type of interlaced camera is well suited to applications where fast moving parts need to be inspected. The vision system can trigger the camera and illumination at the same instant. However, to

avoid the problem of the field offset effect, with high-speed applications, only one field is transmitted, hence the image contains only half the vertical resolution.

Digital cameras for vision systems

A digital camera is ideal for dimensional measurement using vision systems. Its operation is completely different to an analogue camera, in that the analogue to digital (A/D) conversion of the image takes place within the camera. This has significant benefits, as all the unwelcome effects of analogue signal transmission such as noise, interference and line loss are removed. Where a camera is being added to another system it is likely that a USB system will be used since most computer systems can handle these devices without additional hardware. Systems built as dedicated vision metrology systems will almost all use digital cameras as their imaging system, usually using Camera Link communications. The significantly higher bandwidth of Camera Link cables allow for far higher resolution images to be transferred quickly maximising the speed and spatial resolution of the measurements that can be taken.

Linescan cameras

The active area of this camera consists of a single row of pixels. Linescan cameras are mostly used for imaging large, or moving objects. Complete 2D images can be built up by physically scanning the object or camera, with the start controlled by a trigger pulse and the acquisition stopped after a pre-determined number of lines have been scanned. The processing of linescan images does not follow the same rules as those for area scan cameras therefore specific frame grabbers may be required.

Chapter summary

- Be aware of the various camera types.
- Be aware of the importance of linearity.
- Be aware of the various type of analogue camera.
- Know the advantages and disadvantages of digital cameras.
- Know when linescale cameras are used.

Frame grabbers

6

IN THIS CHAPTER

- Analogue frame grabbers
- Digital frame grabbers
- Chapter summary

The frame grabber is the interface between the camera and the control PC. Its task is to assemble a digital image, which can be processed by the computer. There are many commercial frame grabbers available, but their basic operation is as follows:

Analogue frame grabbers

If the video signal is analogue, then the frame grabber must digitise it, using an A/D converter, usually with 8-bit resolution. The sampling interval of the A/D converter, called the pixel clock, can be internally generated or transmitted by the camera. The digitised values are stored in the frame grabber's memory area until a complete image is assembled. The following sections describe the two modes of operation of frame grabbers and how they are used with various camera types.

Live mode

In live mode, the frame grabber continuously overwrites each line in the image, as soon as a new one arrives. This image can be passed through appropriate hardware to the computer graphics card and displayed on the monitor, without the need for an additional video display. This feature is useful when adjusting the illumination and focus. This mode is sometimes referred to as "image grabbing".

Acquisition mode

In this mode, the frame grabber waits for the next VSYNC (Vertical Synchronisation) signal and then starts to digitise and store the new image. The image is complete when the next VSYNC signal is detected and the acquisition stops. The full image may then be fetched by the image processing software from the frame grabber's memory. This mode is sometimes referred to as "image snapping".

Use with a standard video camera

The signal from a standard video camera consists of the odd field first (lines 1, 3, 5...), then the even field (lines 2, 4, 6...). These lines must be stored in the correct sequence in the frame grabber memory. If the image processing software requests the image just after a VSYNC signal, it can take up to 80 ms since the frame grabber will have to wait a full frame, until the next VSYNC signal, to start acquisition. This type of camera may therefore not be suited to high speed image processing.

Use with a progressive scan camera

The frame grabber receives the full frame, in sequence, from this type of camera so no time is lost interlacing the half frames, as with a standard video camera. The transmission time of the full frame may be half that of the standard video camera.

Use with an asynchronous camera

The frame grabber can receive the signal from an asynchronous camera as either half, or full frame. As asynchronous cameras send a new image when triggered, the frame grabber waits for the next VSYNC signal and then stores the image.

Use with a line scan camera

The type of frame grabber used to digitise and store the image from a line scan camera, is different to that described in chapter 6, in that it does not conform to the standard video convention. Line scan cameras are usually used with moving objects and hence, new frames are externally triggered and created line by line with a finite, pre-determined length. Thus, there are no VSYNC signals within the video signal, so the frame grabber must be able to process the various external trigger inputs from the camera or control electronics.

Digital frame grabbers

As the title implies, a digital frame grabber does not need to sample the analogue signal from a camera, as the input is already digitised. Consequently, the design of such frame grabbers is simpler. All digital cameras are progressive or line scan cameras, so each line is stored sequentially with the frame start and line start signals set on individual data lines.

Chapter summary

- Be aware of the various modes for analogue frame grabbers.
- Be aware of the difference between analogue and digital frame grabbers.

Making measurements

7

IN THIS CHAPTER

- Capturing a good image
- Obtaining the pixel calibration
- Setting the correct detection threshold
- Quantifying the effects of distortion and magnification errors
- Sources of measurement uncertainty
- Chapter summary

Now that we have a properly illuminated object and the ability to image it, we are in a position to begin the process of making measurements using the image processing software. The first action to be taken is to calibrate the camera to convert the pixel spacing into units of length. Therefore, a traceable calibration standard or object with known dimensions is required. Before choosing this, it is important to remember that the ideal calibration standard for any application is one with similar dimensions, appearance and texture to the artefacts to be measured.

Chapter 7 describe the processes used to calibrate a Leitz Ergolux AMC microscope, fitted with a 1024×1024 Pulnix digital camera and a Leica QM550 CW image analyser. Whilst there may be some variations in manufacturer terminology and facilities, the calibration and measurement processes described in these sections are essentially applicable to all microscopy and macroscopy applications using vision systems.

Basic Precautions

Cleanliness is vital for all dimensional measurements and is especially important for vision measurements. Dust and fibres on the image can cause serious problems for accurately placing a point. Therefore it is good practice to always use lint free gloves, wear clothing made of synthetic fibres and to work in an environment which is as dust free as possible.

Choosing the right type of measurements

Before making any measurements, it is first worth considering some of the different types of dimensional measurements that can be made. When using a binary image (see chapter 7, Setting the correct detection threshold) it is likely that most measurements will be point to point. For example, the diameter of a circular spot may be given by the longest line of detected pixels in the object. This is known as a feret diameter and is akin to a calliper measurement. These types of measurement are easily obtainable from the vision system, and for most applications have an acceptable accuracy of ± 2 pixels. If higher accuracy is required, then the diameter of the spot may be derived from area measurements. Sub-pixel accuracy is readily achievable by this method, as the vision system effectively averages the diameter of many feret measurements within the detected area. This type of measurement is not restricted to circular features, but may also be applied to objects with linear features. Although making dimensional measurements from the detected area requires a little more processing time, the high speed of today's processors, means that most applications can benefit from this type of image processing.

Capturing a good image

The microscope is set up and the region of interest imaged, in this case a calibrated scale, in accordance with the instructions given in chapter 2. The illumination intensity is adjusted to give the maximum dynamic grey scale range (see chapter 7, Setting the correct detection threshold) without saturating the camera. Most vision systems have the facilities to show saturated areas by filling with a colour and to display the dynamic grey scale range as an aid to setting up the correct illumination intensity. Figure 27 shows both a normal and a saturated image.

At this point, it is worth discussing shading correction. This software-generated filter removes the effects of an uneven field of illumination, perhaps due to the illumination source, or even dirt on the optics or camera. When using shading correction, you will need to check and re-set it each time you change the illumination conditions. This will ensure the measurement results produced are influenced as little as possible by external factors. To set the shading correction, select the relevant menu in the software, which should prompt you to set up a blank field, that is, the same field of view, without the object you wish to measure. Once this is done, the software will calculate the uneven illumination across the field and establish a filter to adjust for it. This filter is particularly useful for correcting small variations in intensity. If the image shows large unevenness in the field of illumination, then the user should examine and if necessary, modify and improve the illumination system. Shading correction must never be used to correct for poor system design.

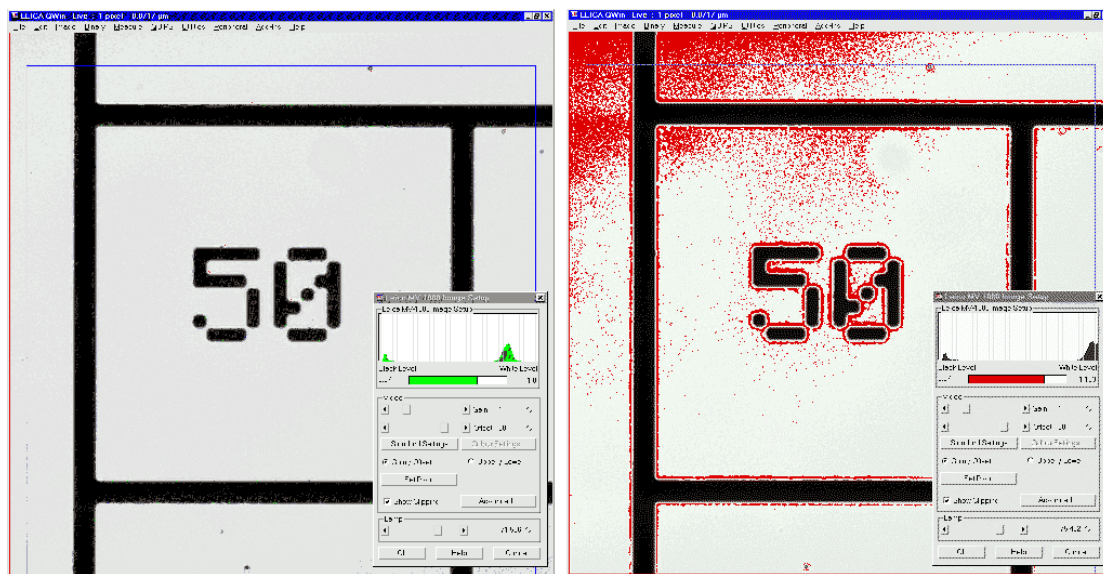


Figure 27: Normal and saturated image illumination.

Obtaining the pixel calibration

All types of vision system software have calibration menus to relate the pixel size to units of length. A grid is useful for calibration of the system, as it can also be used to detect any gross image distortion (see Appendix A.1.1 for further information on calibration artefacts for vision systems). An appropriately sized square should be focused and imaged on the screen. The calibration menu is then selected and a variable frame is used to denote the line centres of the maximum pitch visible, as shown in figure 28. (Some software packages use point-to-point markers instead of a variable frame).

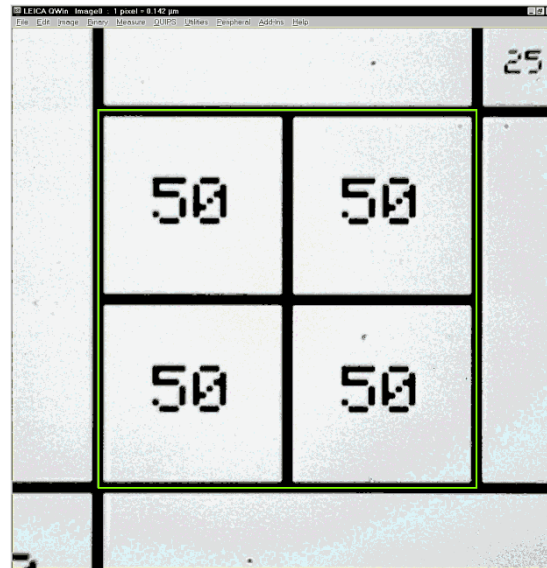


Figure 28: Calibrating the image pixel size.

The calibrated value for the pitch is then entered and the system calculates the real world pixel size. This process is repeated with the scale oriented on the Y-axis, to check the squareness of the calibration, as the camera may not have square pixels. Failure to account for this may introduce significant errors into the measurements. Most systems can produce a software-generated grid. If this grid is superimposed on the image of the graticule grid, any large-scale image distortions will become evident.

Setting the correct detection threshold

After calibrating the system, detecting objects will require setting a threshold. A vision system performs measurements by detecting changes in intensity and hence, the contrast of a feature *e.g.* a black spot against a white background. As each pixel has an 8-bit grey scale intensity value range, 0 being black and 255 white, the user can define a threshold on the grey scale so that regions with intensity above or below that value can be detected. In this way, a binary image is created, whereby pixels with a greyscale intensity value below the threshold are assigned a binary 0, and those above, a binary 1. Depending on whether bright or dark features are to be measured, adjacent detected pixels are grouped together to form a detected feature. Modern vision systems may have the facility to perform grey image processing of features, but for the purposes of this guide, only binary image processing will be covered. Figure 29 shows a typical intensity profile of a dark feature on a bright background. The maximum intensity range of the camera is 0-255 greyscale, but the actual dynamic range of the image may well be less, especially if there is low contrast.

The correct threshold level should be calculated from the image grey scale range. This is called normalising the intensity threshold. For most vision systems, where the optical magnification is less than 20 $\times$, the 50 % normalised threshold should be used. The effects of coherence from the illumination on the true edge position of a feature can be neglected at this scale, as it is well below the measurement uncertainty achievable. The formula for calculating the 50 % threshold is given in equation (14):

$$t = b + (a - b)/2 \quad (14)$$

Where: t = Grey scale intensity threshold;
 b = Mean dark level intensity;
 a = Mean bright level intensity.

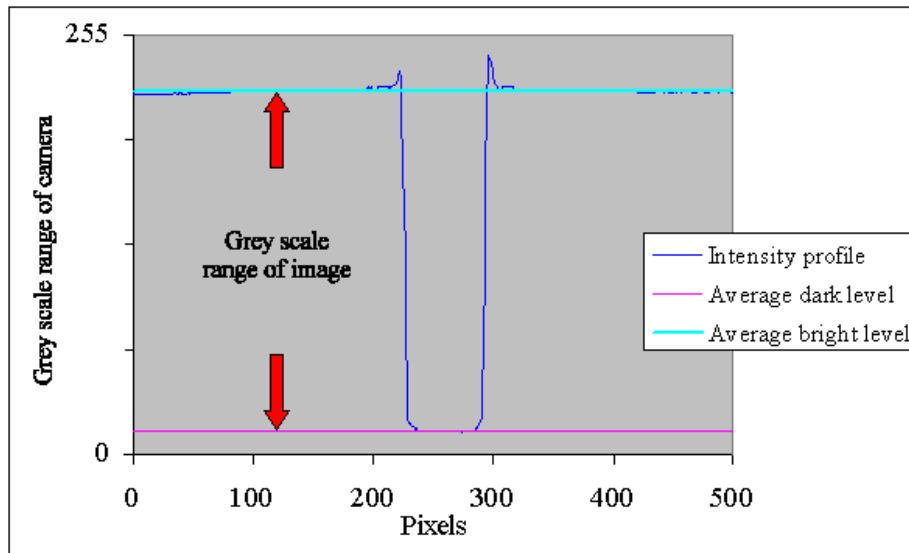


Figure 29: Intensity profile of a dark line on a bright background.

For high power microscopy, the true edge of a feature will be located at some point between the 25 % - 50 % intensity level, as the illumination will be partially coherent (see chapter 2). Under these conditions, the correct threshold may be found experimentally, by measuring the dimensions of a calibrated feature at varying thresholds within the 25 % to 50 % range. The formula for calculating the true edge threshold is given in equation (15).

$$t = i(b + (a - b)) \quad (15)$$

Where: t = Grey scale intensity threshold of the camera;
 i = True edge intensity threshold, expressed as a decimal fraction, *i.e.* 30 % = 0.3;
 b = Mean dark level intensity;
 a = Mean bright level intensity.

It is worth noting that the intensity profile in Figure 29 is of a straight edge and is the average profile over 500 pixel rows on the y-axis. Figure 30 shows the comparison of an averaged intensity profile and the profile of an edge along a single row of pixels. The difference between the two calculated 50 % thresholds is only 4 grey scale values, and for most applications, is negligible. However, where possible, straight edges and averaging should be used, as the noise level on the profile is reduced and the dynamic grey scale range is more accurate.

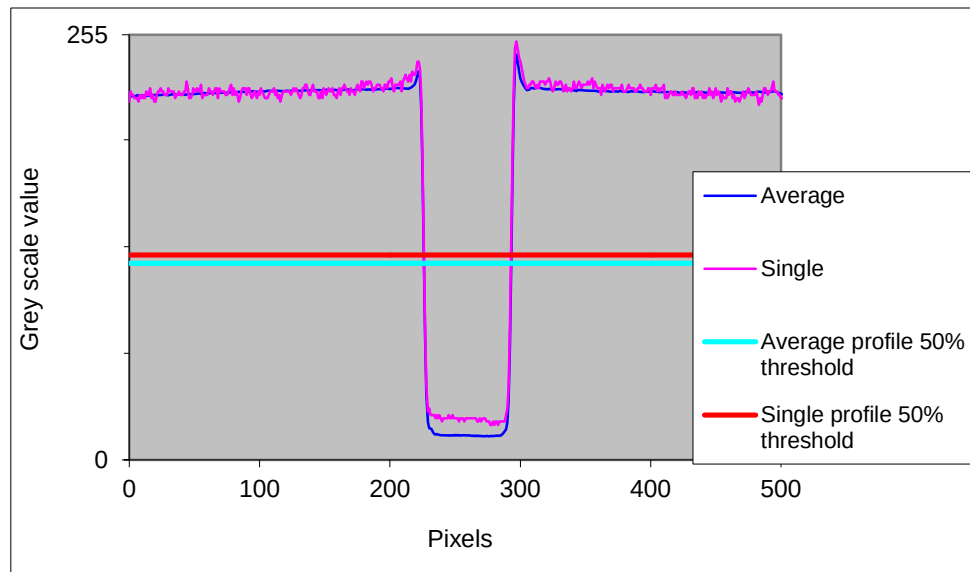


Figure 30: Comparison of average intensity profile with a single pixel line intensity profile.

Quantifying the effects of distortion and magnification errors

Now that the camera has been calibrated and the correct threshold determined, the useable measurement area must be identified. Localised magnification errors are quite common and knowledge of where and by how much the scaling breaks down, allows the determination of the usable measuring area of the image. This is done by imaging an array of calibrated spots, or other suitable standard such as the NPL Optical Dimensional Standard (ODS), over the entire image, as shown in figure 31. (For more information on the ODS and other standards manufactured by NPL see Appendix A.1.1). The diameters of the spots are then measured and any deviation in the sizes of the spots can be seen by comparison with the calibrated values. Measurements must be made rather than direct visual observations because screen distortions may affect judgment.

Errors due to distortion are usually found at the edge of the field of view. These errors may be quantified by measuring the diameters, or centre-to-centre pitches, of the array of spots and comparing them to the calibrated values. It is also possible to perform the pixel calibration using this method and this can provide a more accurate and reliable calibration value for the system, as the centroids of the spots are determined with sub-pixel accuracy. Both axes may be calibrated at the same time and an error map produced very quickly for the entire image area. Once the useable area of the screen has been determined, the pixel calibration should be repeated within that area to minimise errors.



Figure 31: NPL's ODS, which contains patterns specifically designed to identify and quantify errors in a range of optical systems.

Sources of measurement uncertainty

If a vision system is being used as a comparator, then detailing the sources of uncertainty is straightforward. If the system is used for measurement, relying on the pixel calibration, then a little more work is required. The following two examples, which involve the measurement of dark features against a bright background, illustrate these two measurement approaches. It should be noted that vision systems are not restricted to just performing simple measurements on images of this kind alone, but can of course deal with images with far more complex features. The simple nature of the examples that follow is purely to give clarity to the analysis of the sources of uncertainty.

Firstly, let us consider a vision system used as a comparator to measure the diameters of a series of spots, ranging in size from $3\text{ }\mu\text{m}$ - $48\text{ }\mu\text{m}$. The calibration standard is an identical series of spots, the diameters of which have been calibrated and are traceable to the national standard of length. The spots were measured using a Leitz Ergolux AMC microscope with a $100\times$ objective, a 1024×1024 square pixel Pulnix digital camera and a Leica QM550 CW image analyser. As this is a comparative measurement, the detection threshold is set at 50 % of the camera grey scale.

Before each unknown spot is measured, the vision system must be used to measure the calibration standard. This calibration gives the measurement its traceability. The same software routine is used for both the known (calibration standard) and unknown (test) spots with each spot measured three times in the same position in the image. This means that any errors, perhaps due to the effects of distortions or magnification, will be seen in the standard deviation of the measurements. The Equivalent Circle Diameter was measured, which is the diameter of a perfectly round circle derived from the area of the detected spot. This measurement is preferable to feret (calliper) measurements as it effectively gives sub-pixel

accuracy. The deviation of the measurements on the calibrated spots from the true values gives the calibration offsets, as shown in table 8 and graphically, in figure 32.

Table 8 Results from measurement of the calibration standard.

Spot	Run 1	Run 2	Run 3	Standard deviation	Average	Certified values	Offset
1	47.839	47.841	47.849	0.005	47.843	47.66	- 0.183
2	33.716	33.718	33.721	0.003	33.718	33.57	- 0.148
3	23.794	23.8	23.807	0.007	23.800	23.65	- 0.150
4	16.785	16.792	16.799	0.007	16.792	16.62	- 0.172
5	11.805	11.807	11.809	0.002	11.807	11.63	- 0.177
6	8.238	8.248	8.258	0.010	8.248	8.08	- 0.168
7	5.782	5.782	5.79	0.005	5.785	5.61	- 0.175
8	4.003	4.018	4.023	0.010	4.015	3.84	- 0.175
9	2.738	2.746	2.755	0.009	2.746	2.57	- 0.176

All dimensions in μm .

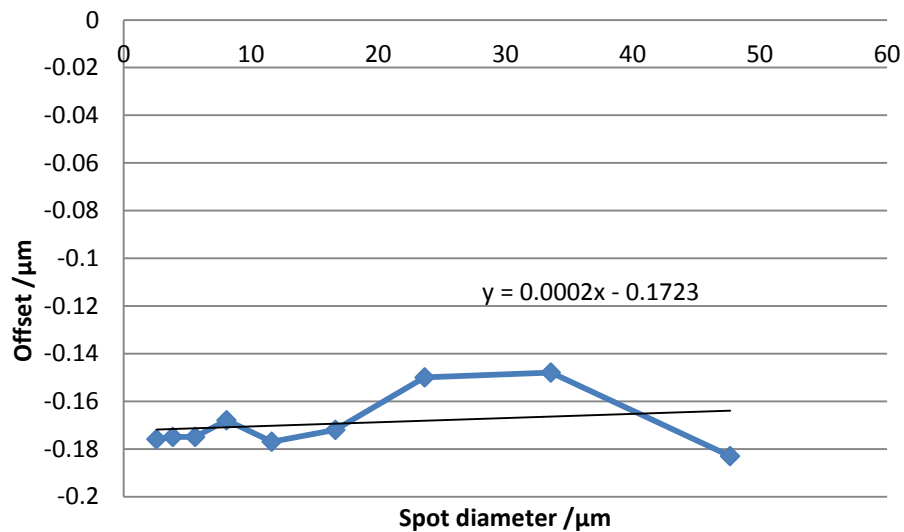


Figure 32: Calibration offsets, with the coefficients of the linear fit displayed.

The unknown spots were then measured three times in exactly the same way, without changing the illumination conditions. The measured diameters were corrected using a linear fit applied to the calibration offsets, thereby giving the true diameters of the unknown spots. The linear fit is of the form $y = mx + c$ and the results are shown in table 9.

Table 9 Results from measurements of the unknown spots.

Spot	Run 1	Run 2	Run 3	Standard deviation	Average	Corrected values
1	47.724	47.732	47.722	0.005	47.726	47.56
2	33.602	33.615	33.598	0.009	33.605	33.44
3	23.686	23.697	23.681	0.008	23.688	23.52
4	16.68	16.683	16.67	0.007	16.678	16.51
5	11.692	11.702	11.688	0.007	11.694	11.52
6	8.14	8.149	8.133	0.008	8.140	7.97
7	5.677	5.684	5.666	0.009	5.675	5.50
8	3.897	3.904	3.884	0.010	3.895	3.72
9	2.626	2.628	2.614	0.008	2.622	2.45

All dimensions in μm .

The measurement uncertainties were then calculated, as follows:

- The uncertainty due to the calibration of the standard is $\pm 0.08 \mu\text{m}$, at a coverage factor $k = 2$, for a 95 % confidence level. Dividing by 2 gives the standard uncertainty, $0.04 \mu\text{m}$, where $k = 1$.
- The worst-case standard deviation of the measurements of the vision system is $0.01 \mu\text{m}$. Since each spot was measured 3 times, we divide $0.01 \mu\text{m}$ by the square root of 3, giving the standard uncertainty of the mean (or standard deviation of the mean) as $0.006 \mu\text{m}$. Where N measurements are made, the standard deviation is divided by $\sqrt{N}$.

The measurement uncertainty due to the repeatability of the vision system must be considered twice, firstly when calibrating the machine against the standard and secondly when measuring the unknown spots.

$$u_c = \sqrt{0.04^2 + 0.006^2 + 0.006^2} = 0.041 \mu\text{m}.$$

So, the combined standard uncertainty of the measurements, by summing in quadrature, is $0.041 \mu\text{m}$. The expanded uncertainty for 95 % confidence, is given by multiplying the standard error by $k = 2$, giving $0.082 \mu\text{m}$.

For the second example, the spots were measured three times, obtaining the measurement traceability from the pixel calibration of the system. The correct detection threshold was determined for these measurements and was set at 33 % of the normalised grey scale. Table 10 shows the results.

Table 10 Results of spot measurements, traceable to the system calibration.

Spot	Run 1	Run 2	Run 3	Standard deviation	Average	True diameter	Difference
1	47.896	47.896	47.895	0.000 5	47.896	47.83	0.066
2	33.780	33.778	33.778	0.001 1	33.779	33.72	0.059
3	23.865	23.859	23.855	0.005 0	23.860	23.81	0.050
4	16.869	16.856	16.853	0.008 5	16.859	16.78	0.079
5	11.851	11.841	11.841	0.005 7	11.844	11.78	0.064
6	8.330	8.329	8.325	0.002 6	8.328	8.26	0.068
7	5.794	5.790	5.788	0.003 0	5.791	5.72	0.071
8	3.990	3.980	3.975	0.007 6	3.982	3.89	0.092
9	2.752	2.745	2.745	0.004 0	2.747	2.66	0.087

Let us consider the uncertainty contributions that apply to this set of measurements.

- The vision system was calibrated with an optical scale whose uncertainty due to the calibration of the scale is $\pm 0.10 \mu\text{m}$, at a coverage factor $k = 2$, for a 95 % confidence level. Dividing by 2 gives the standard uncertainty, $0.05 \mu\text{m}$.
- The pixel calibration value, using a $100\times$ objective, was $0.0717 \mu\text{m}$ per pixel. The error due to manual calibration of the pixel size, using the software-generated frame is up to ± 2 pixels and affects both axes. Combining the errors in X and Y, in quadrature, gives an uncertainty of $\pm 0.2 \mu\text{m}$. This uncertainty is deemed to have a rectangular distribution, as the measurements are equally as likely to be undersized, as oversized. Dividing $\pm 0.2 \mu\text{m}$ by 2 gives the half-width, which is then divided by $\sqrt{3}$, resulting in a standard uncertainty of $0.058 \mu\text{m}$.

$$\sqrt{(0.072 + 0.072)^2 + (0.072 + 0.072)^2} = 0.02 \mu\text{m}$$

$$\frac{0.02}{2\sqrt{3}} = 0.058 \mu\text{m}$$

- The magnification and distortion errors across the entire image were measured and found to be, in the worst case, $\pm 0.05 \mu\text{m}$ and affects both axes. Combining the errors in X and Y, in quadrature, gives an uncertainty of $\pm 0.071 \mu\text{m}$. This uncertainty is deemed to have a rectangular distribution, as the measurements are equally as likely to be undersized as oversized. Dividing $\pm 0.071 \mu\text{m}$ by 2 gives the half-width, which is then divided by $\sqrt{3}$, resulting in a standard uncertainty of $0.02 \mu\text{m}$.

$$\sqrt{(0.05)^2 + (0.05)^2} = 0.071 \mu\text{m}$$

$$\frac{0.071}{2\sqrt{3}} = 0.02 \mu\text{m}$$

- Combining the above terms in quadrature gives

$$\sqrt{0.05^2 + 0.058^2 + 0.02^2} = 0.079 \mu\text{m}.$$

- The standard deviation each of the measurements must also be taken into account (for simplicity the maximum value, $0.0085 \mu\text{m}$, is used in the example). Since each spot is measured 3 times we divide it by the square root of 3, giving the standard uncertainty of the mean (or standard deviation of the mean). Where N measurements are made, the standard deviation is divided by $\sqrt{N}$.

So the combined standard uncertainty for each of the measurements, by summing in quadrature, is $\sqrt{0.079^2 + (\sigma_{n-1}/\sqrt{3})^2}$, where σ_{n-1} is the standard deviation of the measurements. This gives us a standard uncertainty of $\pm 0.079 \mu\text{m}$ for the measurements and the expanded uncertainty is $\pm 0.16 \mu\text{m}$, for a 95% confidence level.

By comparing results, it can be seen that the measurement uncertainty when using the system as a comparator is smaller than when using it in a direct measurement mode. For highest accuracy measurements vision systems should therefore be used as comparators whenever possible. However, it is also worth noting that the accuracy of the results from the direct measurement mode example is well within the measurement uncertainty. It is, of course, up to the end user to decide what level of accuracy and uncertainty is acceptable for his particular measurements.

The analysis above concentrates on the basic errors specific to vision systems. Other sources should also be considered by the operator.

Thermal effects on the artefacts or on the scales of the vision system (whether they are artefact or signal based, *e.g.* and interferometer) will, in most environments, be the dominant uncertainty contribution so it is good practice to carry out dimensional metrology in a temperature controlled environment where possible. Ideally the artefacts should be measured at 20°C which is the international standard temperature for dimensional measurements. Some systems may include automatic thermal compensation corrections based on measured deviations from standard temperature. In this case the error of the temperature measurement device should be considered in the uncertainty calculation.

Some multi-axis systems, in particular Vision Co-ordinate measuring machines (VCMMs), may have a MPE or Maximum Permitted Error in their specification. In some cases this may vary depending on how many and which axes are being used in the measurement.

It must be clearly understood the MPE of the machine is not the same as the uncertainty of a measurement made with that machine. The MPE may be useful as a term in the uncertainty calculation where no better verification has been carried out but it is always better practice to use a traceably calibrated artefact to verify the machine.

Further information regarding the calculation of uncertainty may be found in the NPL Measurement Best Practice Guide No. 11, '*A Beginner's Guide to Uncertainty of Measurement.*'

Chapter summary

The contents of this chapter can be summarised as follows:

- Choose the right type of measurement.
- Capture a good image.
- Perform a pixel calibration.
- Set the correct threshold.
- Quantify the effects of distortion and magnification errors.
- Know the sources of measurement uncertainty.

Summary

8

IN THIS CHAPTER

- Summary

This measurement good practice guide has provided an overview of the various considerations when making measurements with a vision metrology system.

Making accurate measurements is as much about being confident of the *measuring system's*¹ performance history as it is about its day-to-day repeatability. Whilst modern vision systems generally exhibit excellent measurement repeatability and reproducibility, measurement errors can still be produced. This can be due, for example, to the use of incorrect or inappropriate measurement practices, technical problems with the equipment, calibration errors, changes in environmental conditions or operator errors. In order to minimize such problems and ensure that accurate measurements are made, users are recommended to take steps to regularly monitor the performance of their *measuring systems* by acquiring and analysing statistics on repeatability and reproducibility. This will enable departures from 'the normal' to be spotted at an early stage and allow action to be taken to identify and correct the source of the errors in order to return the *measuring system* to its desired operating state.

The contents of this guide can be summarised as follows

- Know the basics of microscopy.
- Know the basics of macroscopy.
- Know the basics of illumination sources and configurations.
- Know about the different types of lenses.
- Know the effect of different types of camera.
- Know about frame grabbers.
- Know how to make a good measurement.
- Know the basics of Uncertainty of Measurement.

¹ The *measuring system* here includes the vision system, any associated equipment or accessories required for the measurement and the operator.

Glossary of terms

9

IN THIS CHAPTER

- A glossary of terms.

Glossary of terms

Terms defined below are based on the VIM, 3rd edition, JCGM 200:2008 (*International Vocabulary of Metrology - Basic and General Concepts and Associated Terms*) and ISO 10360 Part 7.

CMM	A measuring system with the means to move a probing system and capability to determine spatial coordinates on a workpiece surface.
Digital camera	A camera that encodes an image digitally and store it for later reproduction
Eyepiece	the lens or combination of lenses in an optical instrument through which the eye views the image formed by the objective lens or lenses; ocular.
Field of view (FOV)	Area viewed by the imaging probing system
Imaging probe CMM	CMM equipped with an imaging probing system; Also known as VCMM (Vision CMM)
Imaging probing system	probing system which creates measurement points through the use of an imaging system
Measuring plane	two-dimensional plane defined by the FOV of an imaging probing system
Numerical Aperture (NA)	the numerical aperture (NA) of an optical system is a dimensionless number that characterizes the range of angles over which the system can accept or emit light
Objective lens	the lens or system of lenses in a telescope or microscope that is nearest the object being viewed
Ram	The component of a CMM that carries a probing system. Also called the quill.

Health and safety

10

IN THIS CHAPTER

- Mechanical
- Hazards associated with laser illumination
- Chemical

When operating a vision system any local safety rules should be adhered to and a risk assessment undertaken before starting the work. If working at a customer's site be aware of any evacuation procedures and any extra risks such as moving vehicles and overhead cranes. Some specific things to look for when carrying out a risk assessment are listed below.

Mechanical hazards

Appropriate lifting techniques and equipment should always be used and safety shoes worn. Operators should wear laboratory coats or overalls for safety reasons and to prevent fibres shed from clothing from falling on items being measured.

Machines under direct computer control may move without warning. The operator should stand back from the machine during an automatic run.

Hazards associated with laser illumination

Some systems employ class 2 laser radiation therefore the appropriate laser safety precautions should always be observed. It goes without saying that any users of such systems should be trained in their safe usage. Some general guidance is given in the box below.

NOTE



Important safety information

A rough guide to laser safety stickers would say that any laser system with a visible output of less than 0.2 mW is considered a Class 1 laser and is not dangerous while any visible laser of between 0.2 mW and 1.0 mW output power are considered Class 2 and rely on the blink reflex to protect vision in the event of eyestrike. Class 3R are lasers below 5.0 mW that will cause damage before a blink reflex is triggered. Class 3B refers to power levels above 5.0 mW and can cause permanent damage to eye sight with only a very short exposure. Class 4 involves powers above 0.5 W and can burn skin on contact and can severely damage sight even with diffuse viewing. (For a more detailed description of the classes have a look at BS EN 60825-1 2007.)

Chemical hazards

Chemicals may need to be used for cleaning purposes. Make sure the manufacturer's safety guidance is followed and the relevant personal protective equipment worn. Substances may be covered by the COSHH regulations.

Appendices

11

IN THIS CHAPTER

- Appendix A Links to other useful sources of information.
- Appendix B Further reading.

Appendix A Links to other useful sources of information

A.1 National and International Organisations

A.1.1 National Physical Laboratory

"When you can measure what you are speaking about and express it in numbers you know something about it; but when you can not express it in numbers your knowledge is of a meagre and unsatisfactory kind."

Lord Kelvin, British Scientist (1824 – 1907)



The National Physical Laboratory (NPL) is the UK's national measurement institute and is a world-leading centre of excellence in developing and applying the most accurate measurement standards, science and technology available. For more than a century NPL has developed and maintained the nation's primary measurement standards. These standards underpin an infrastructure of traceability throughout the UK and the world that ensures accuracy and consistency of measurement.

NPL ensures that cutting edge measurement science and technology have a positive impact in the real world. NPL delivers world-leading measurement solutions that are critical to commercial research and development, and support business success across the UK and the globe.

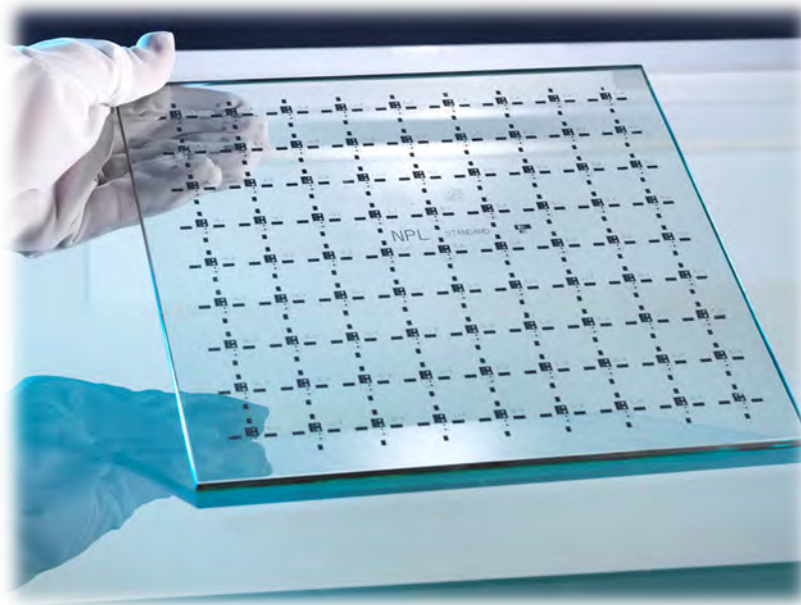
Good measurement improves productivity and quality; it underpins consumer confidence and trade and is vital to innovation. NPL undertake research and shares its expertise with government, business and society to help enhance economic performance and the quality of life.

NPL's measurements help to save lives, protect the environment, enable citizens to feel safe and secure, as well as supporting international trade and companies to innovation. Support in

areas such as the development of advanced medical treatments and environmental monitoring helps secure a better quality of life for all.

NPL employs over 500 scientists, based in south west London, in a laboratory, which is amongst the world's most extensive and sophisticated measurement science buildings.

The National Physical Laboratory is operated on behalf of the National Measurement Office by NPL Management Limited, a wholly owned subsidiary of Serco Group plc. For further information: Switchboard 020 8977 3222 | www.npl.co.uk/contact



For information on high-precision optical dimensional standards for vision systems (including line scales, image analyser standards, 2-D optical standards and photomask linewidth standards) visit the Dimensional and Optical Metrology web pages at http://www.npl.co.uk/npl/length/dmet/services/ms_rsg.html

A.1.2 National Institute of Standards and Technology (NIST)

NIST is the equivalent of NPL in the United States of America. Founded in 1901, NIST is a non-regulatory federal agency within the U.S. Department of Commerce. NIST's mission is to promote U.S. innovation and industrial competitiveness by advancing measurement science, standards, and technology in ways that enhance economic security and improve quality of life.

The NIST web site at www.nist.gov often contains documents relevant to this guide in Adobe PDF.

A.1.3 EURAMET

The European Association of National Metrology Institutes (EURAMET) is a Regional Metrology Organisation (RMO) of Europe. It coordinates the cooperation of National Metrology Institutes (NMI) of Europe in fields such as research in metrology, traceability of measurements to the SI units, international recognition of national measurement standards and related Calibration and Measurement Capabilities (CMC) of its members. Through knowledge transfer and cooperation among its members EURAMET facilitates the development of the national metrology infrastructures.

EURAMET serves the promotion of science and research and European co-operation in the field of metrology.

This is realized by the following measures in particular:

- o development and support of European-wide research co-operation in the field of metrology and measurement standards;
- o development, regular updating and implementation of a European Metrology Research Programme (EMRP);
- o support of members and associates when applying for research funds for the purpose of European cooperative projects;
- o co-ordination of joint use of special facilities;
- o improvement of the efficiency of use of available resources to better meet metrological needs and to assure the traceability of national standards;
- o technical co-operation with metrology institutes beyond EURAMET and with other regional and international metrology organisations;
- o performing the tasks of a Regional Metrology Organisation (RMO) with the objective of worldwide mutual recognition of national measurement standards and of calibration and measurement certificates;
- o promotion and co-ordination of scientific knowledge transfer and experience in the field of metrology;
- o representing metrology at the European level and promoting best practice to policy and political decision makers with regard to the metrological infrastructure and European co-operation;
- o co-operation with European and international organisations responsible for quality infrastructure, in particular by participation in the preparation of harmonized technical documents.

For more information visit the EURAMET web site at: www.euramet.org

A.1.4 Institute for Geometrical Product Specification

More information about GPS can be found at the Institute for Geometrical Product Specification website www.ifgps.com. Click on resources for more information on GPS.

A.2 Networks

A.2.1 Mathematics and Modelling for Metrology (MMM)

MMM is an programme that underpins the NMS, focussing on the use of mathematics and computing in metrology. It aims to achieve a balance between research and development, whilst also extending the range of techniques and applications available to meet the continually changing needs of metrology. The overall aim of the Programme is to tackle a wide range of generic issues, some of which are problems in metrology that require the application of established software engineering practices, whilst others require advances in mathematics, software engineering or theoretical physics. The programme, thus, includes work in metrology, mathematics, software and theoretical physics, with strong links between the various disciplines.

Further details can be found at website: <http://www.npl.co.uk/category/384>

A.3 National and International Standards

A.3.1 British Standards Institution (BSI)

BSI started in 1901 as a committee of engineers determined to standardise the number and type of steel sections in order to make British manufacturers more efficient and competitive. The BSI Group is now the oldest and arguably the most prestigious national standards body in the world and is among the world's leading commodity and product testing organisations. Website www.bsi-group.com.

A.3.2 International Organisation for Standardization (ISO)

The International Organization for Standardization (ISO) is a worldwide federation of national standards bodies from some 140 countries.

The mission of ISO is to promote the development of standardisation and related activities in the world with a view to facilitating the international exchange of goods and services, and to developing cooperation in the spheres of intellectual, scientific, technological and economic activity.

ISO's work results in international agreements that are published as International Standards.

Further information on ISO can be found at: www.iso.ch

The following BS and ISO specifications are relevant to this guide.

BS EN ISO 10360-7:2011 *Geometrical product specifications (GPS). Acceptance and reverification tests for coordinate measuring machines (CMM). CMMs equipped with imaging probing systems*

ISO 10360-1: 2000 *Geometrical Product Specifications (GPS) – Acceptance and reverification tests for coordinate measuring machines (CMM)—Part 1: Vocabulary*

ISO 10360-2: 2009 *Geometrical product specifications (GPS) – Acceptance and reverification tests for coordinate measuring machines (CMM) — Part 2: CMMs used for measuring linear dimensions*

A.4 Traceability

Traceability in measurement is the concept of establishing a valid calibration of a measuring instrument or measurement standard, by a step-by-step comparison with better standards up to an accepted or specified standard. In general, the concept of traceability implies eventual reference to an appropriate national or international standard.

The National Physical Laboratory is the United Kingdom's national standards laboratory. It operates at the heart of the National Measurement System (NMS) which is the infrastructure designed to ensure accuracy and consistency in every physical measurement made in the UK. Chains of traceability link UK companies' measurements directly to national standards held at NPL.

For the majority of industrial applications, companies can establish a link to national measurement standards through the calibration and testing services offered by United Kingdom Accreditation Service (UKAS) accredited laboratories, which are in turn traceable to NPL. However, for challenging or novel measurements to the highest standards of accuracy, which are not catered for by UKAS-accredited laboratories, NPL can often provide a traceable measurement solution directly to industry.

The United Kingdom Accreditation Service is the sole national accreditation body recognised by government to assess, against internationally agreed standards, organisations that provide certification, testing, inspection and calibration services.

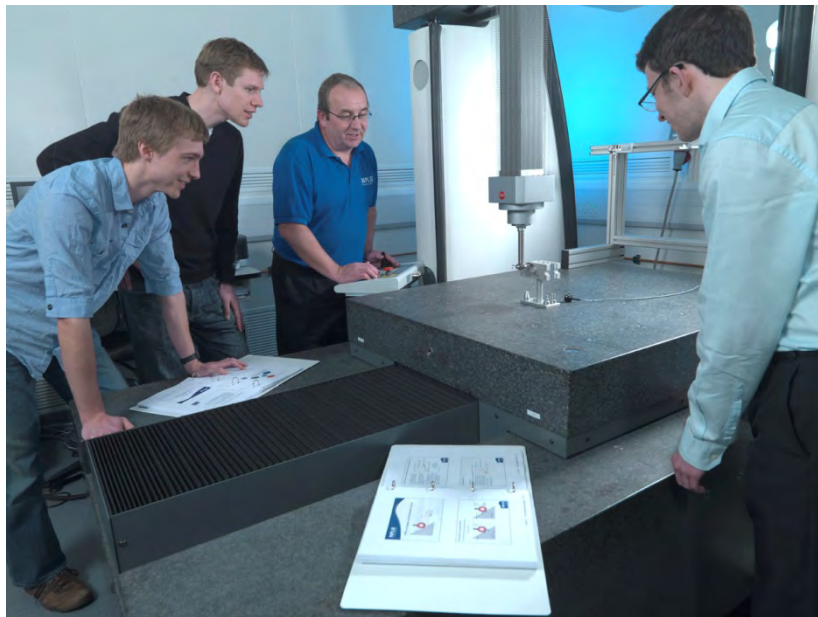
Accreditation by UKAS demonstrates the competence, impartiality and performance capability of these evaluators.

UKAS is a non-profit-distributing private company, limited by guarantee. UKAS is independent of Government but is appointed as the national accreditation body by the Accreditation Regulations 2009 (SI No 3155/2009) and operates under a Memorandum of Understanding with the Government through the Secretary of State for Business, Innovation and Skills.

UKAS accreditation demonstrates the integrity and competence of organisations providing calibration, testing, inspection and certification services.

Further information on UKAS can be found at: www.ukas.com.

A.5 Training courses



A.5.1 Dimensional Measurement Training: Level 1 – Measurement User

A three day training course introducing measurement knowledge focusing upon dimensional techniques.

Aims & Objectives

To provide:

- the underpinning knowledge and expertise for anyone who uses measurement tools or requires an appreciation of the importance of measurement,
- the principle knowledge and practical training for people who are required to use dimensional measurement techniques to complete their daily tasks; and
- the tools to instil and encourage questioning culture.

Enabling:

- An understanding of the fundamentals of standards, traceability, calibration, uncertainty, repeatability, drawing symbols and geometrical tolerances, the importance of the relationship between tolerances and measuring equipment and be able to question the measurement.

Level 1 is applicable to all industrial sectors as a stand-alone qualification or as a building block for further NPL Dimensional Measurement Training levels – 2 & 3.

Course Content**Day 1 - Geometric Product Specification (GPS) A**

Including what is GPS, drawing practice and geometrical tolerances.

Day 2 - Measurement Principles and Methods A

Including successful measurements, standards, traceability, calibration, uncertainty, units, relationship between tolerances and measuring equipment using micrometers and callipers, repeatability and reproducibility of measurements.

Day 3 - Measurement Principles and Methods B

Including the relationship between tolerances and measuring equipment by the use of height gauges, dial test indicators, dial gauges, plug gauges, gap gauges and temperature effects.

NB: Fundamental Measurement Calculation is incorporated into all 3 days including powers, scientific notation and triangles. This is achieved by understanding the relationship of these calculations when applied to tolerance zones and practical measuring tasks.

A workbook of evidence must be completed successfully during the training course and, where required, post assessment tasks can be set for each individual to be completed in the workplace.

A.5.2 Dimensional Measurement Training: Level 2 - Measurement Applier

A four day training course for those who have a good basic understanding of measurement principles gained through the Level 1 training course.

Aims & Objectives

To provide:

- the underpinning knowledge and expertise for anyone who uses measurement tools or requires an appreciation of the importance of measurement,
- the principle knowledge and practical training for people who are required to use co-ordinate measurement techniques to complete their daily tasks; and
- the tools to instil and encourage questioning and planning culture

Enabling:

- a visible return on investment for a manufacturing organisation in the form of various production cost savings and an upskilled workforce,
- a reduction in re-work time and waste on the production line - faults and problems will be detected earlier in the production process; and
- An in-depth appreciation of *why* measurement is carried out and not simply *how*

Level 2 is applicable to all industrial sectors as a stand-alone qualification or as a building block for further NPL Dimensional Measurement Training levels – 3 & 4.

A workbook of evidence must be completed successfully during the training course and, where required, post assessment tasks can be set for each individual to be completed in the workplace.

Course Content

Geometric Product Specification (GPS) B

Content covered:

GPS standards; Envelope tolerance; Size Principles; ISO Limits and Fits
Projected tolerance; Free state condition; Virtual condition; Maximum
Material Condition principles; Geometrical tolerancing measurements using
first principle measuring equipment; Surface texture principles.

Measurement Principles and Methods C

Content covered:

Calibration; Uncertainties; Traceability; Procedures; First Principle
Measurement; Angle plate; Gauge blocks; Surface plate; Height micrometer;
Sine bar or sine table.

Process Control A

Content covered:

Statistical Process Control theory; Variation – common, special causes;
Prevention versus detection; Collecting and calculating data when using
measuring tools; Callipers; micrometers; Basic charts – Tally chart/Frequency
Table, Histogram, Control Chart; Reacting to variation; Benefits of process
control; Standard deviation; Capability indices; Fundamentals of Gauge R&R.

Measurement Principles and Methods D

Content covered:

Taper calculations; Angles; Diameters; Searching for triangles; Chords;
Radians; Manipulation of formula.

Co-ordinate Principles A

Content covered:

Application of equipment: First principles; Co-ordinate Measuring Machine;
Optical and vision machines; Articulating arm; Laser tracker; Projector;
Microscopes; Height gauge with processor; Contour measurement equipment.

Machine performance: Calibration standards; Self-verification/artefacts;
Measurement volume.

Alignment Techniques: 321/point system alignment; Flat face alignment;
Axes alignment; Car line/engine centre line.

Machine appreciation: Ownership; Care; Respect; Cost; Contribution to the
business.

Work Holding: Fixturing; Rotary table; Clamping; How to hold the part;
Influence of component weight, size, shape; Free state; Restrained state.

Co-ordinate geometry: Points; Plane; Line; Circle; Cylinder; Cone; Sphere;
Ellipse.

Sensor Types: Probing Strategies; Relevant standards; Environment.

Measurement Strategies: Number of points; Partial arc; Contact/non contact.

Co-ordinate methods A (OEM Training - equipment specific)

Content covered:

First principles; Co-ordinate Measuring Machine; Optical and vision machines; Articulating arm; Laser tracker; Projector; Microscopes; Height gauge with processor; Contour measurement equipment.

A.5.3 Mitutoyo training courses

The Mitutoyo Institute of Metrology offers qualifications and training in over thirty metrology related subjects. Mitutoyo training programmes are vocation based and are accredited with the Open College Network (<http://www.nocn.ac.uk>) for a qualification in Dimensional Metrology. These credits in turn, contribute towards the evidence route of the Technical Services Engineering NVQ recently accredited by EMTA (Engineering and Maritime Training Authority). These courses are recognised nationally and are available in various areas of metrology.

See the Mitutoyo training pages <http://www.mitutoyo.co.uk/service-and-support/training/> for more information.

A.5.4 NPL E-Learning

Access over a century of **measurement knowledge** and **state-of-the-art techniques**, quality assured from the UK's National Measurement Institute. NPL's new e-Learning programme delivers measurement training, globally accessible across PCs and mobile devices, helping to provide confidence, value and performance from your measurement systems.

Engage with cost-effective on-demand content, globally accessible through an easy-to-use professional solution, compatible across devices.

NPL e-Learning offers:

- metrology training courses;
- free online open units; and
- free *Glossary of Metrology Terms*.

Ready for:

- apprenticeship programmes;
- national curricula; and
- workplace learning schemes.

Measurement just got simpler, and is now available to you **whenever you want and wherever you like – sign up now for free.**

<http://www.npl.co.uk/e-learning>



- Save time - Reduce time away from the job and fit training into busy work schedules
- Save money - Save travel costs and adjust training to your own schedule
- Take the classroom with you - Have your lessons anytime, anywhere
- Control your learning - Sequence your own learning and access only the materials you require
- Own your progression - Assess your progress and receive immediate feedback

Appendix B Further reading

NPL Course Notes: Optical Microscopy for Dimensional Measurement in Microelectronics, 1981

Industrial Image Processing, 2013, ISBN-10: 3642339042 by C Demant, B Streicher-Abel and P Waszkewitz

NPL Measurement Best Practice Guide No. 11, A Beginner's Guide to Uncertainty of Measurement, 1999, ISSN 1368-6550

Handbook of Computer Vision Algorithms in Image Algebra, Second Edition by [Joseph N. Wilson](#), [Gerhard X. Ritter](#)

Digital Image Processing: Principles and Applications by [Gregory A. Baxes](#)

Algorithms for Image Processing and Computer Vision, Second Edition by [James R. Parker](#)

Practical Algorithms for Image Analysis: Descriptions, Examples, and Code by [Michael Seul](#), [Lawrence O'Gorman](#), [Michael J. Sammon](#)

Computer Vision and Applications: A Guide for Students and Practitioners (With CD-ROM) edited by [Bernd Jahne](#) , [Horst Haussecker](#)

The Image Processing Handbook, Sixth Edition by [John C. Russ](#)

Computer-Assisted Microscopy: The Measurement and Analysis of Images by [John C. Russ](#)

Other information is published regularly in Machine Vision and Applications, Image Processing Europe, Quality Today, Measurement Science and Technology, Metrologia, Measurement and Precision Engineering.

<http://www.ukiva.org/>, UK Industrial Vision Association website. This site contains a members list (users and manufacturers) with excellent links and contact details, publication and case study information.

<http://www.bmva.org/>, British Machine Vision Association website. This site contains publication and case study information.

<http://www.dai.ed.ac.uk/CVonline/>, CVonline: The Evolving, Distributed, Non-Proprietary, On-Line Compendium of Computer Vision. Editor: Robert B. Fisher, Division of Informatics, University of Edinburgh.