Measurement of cutter marks on planed wood surfaces with machine vision methods

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Measurement of cutter marks on planed wood surfaces

with machine vision methods

by

Diming Yang

A Doctoral Thesis
Submitted in partial fulfilment of the requirement
for the award of Doctor of Philosophy
of Loughborough University

May 2006

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Abstract

Cutter marks on machined wood surfaces are generated by the planing and moulding wood machining process. Cutter mark defect is referred to as inconsistency of widths and heights of the cutter mark waves, which is critical in some sectors of the woodworking industry. Machining speeds in the woodworking industry are remarkably high. In order to meet the demands of high efficiency and high quality, in-process measurement of cutter marks on machined wood surfaces is highly desirable.

Machine vision technology is being widely used in various quality control applications due to its advantages of non-contact and high data rates. Clearly, machine vision is also highly suitable for in-process measurement of wood surfaces. This research focuses on using machine vision techniques to measure cutter marks on planed wood surfaces.

Before machine vision methods are investigated, a laser profilometer is investigated for its feasibility of measuring cutter marks on wood surfaces. Although the profilometer cannot be used for in-process applications, it provides a good reference for other methods.

Three major machine vision methods and their variations are investigated: They are the Light Sectioning method and the Differential Light Sectioning method, the Shadow Analysis method and the Multi-Angle Shadow Analysis method, the two-image Photometric Stereo method and the one-image Shape From Shading method.

Nine samples, made of three species of wood - beech, oak and ramin, with cutter mark widths of 1.5mm, 2mm and 2.5mm generated on the samples of each species, are tested. Surface profiles measured with all the machine vision methods are compared to the reference profiles measured with the laser profilometer.

Experiments indicate that the Light Sectioning method and the Shadow Analysis method both work to some extent, the Differential Light Sectioning method and the Multi-Angle Shadow Analysis method are not practical; the two-image Photometric Stereo method is the most reliable machine vision method among all the methods investigated; and the one-image Shape From Shading method needs further studies.

Key words: wood surface quality, cutter mark, machine vision, light sectioning, shadow analysis, photometric stereo
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1. Introduction

1.1 Rotary machining of timber

In today’s wood working industry, planing and moulding are two primary machining processes. Planing process employs rotary cutter heads holding straight cutters to produce flat surfaces, while moulding process employs shaped cutters to produce profiled surfaces. These two types of rotary machining processes are similar to the up-milling process in metal working industry. Fig. 1-1 is a schematic illustration of the rotary machining of timber.

![Cutterhead](image)

Fig. 1-1 The kinematics of rotary machining process

As shown in Fig. 1-1, the cutterhead rotates anticlockwise around a spindle parallel to the timber top surface. The knives on the cutterhead cut the wood in turn while the workpiece is feeding from the right to the left. The rotary speed of a cutterhead is typically in the range from 6,000 rpm to 15,000 rpm [1], with cutter tip velocities within the range 30-125 m/s. The feed speed of timber can be up to 200 m/min [2], typically ranging from 5 to 120 m/min [3]. Both the cutting speed and the feed speed are much higher than those applied in the metal working industry. The number of cutters on a cutterhead is usually from 2 to 20 [1].

Planing and moulding machines usually comprise a series of horizontal and vertical cutterheads, as illustrated in Fig. 1-2. Fig. 1-3 is an illustration of a cutterhead and the accessories around it.
1.2 Cutter marks

Due to the kinematics of the rotary cutting process, as shown in Fig. 1-1, cutter marks are left behind on the machined surface. Cutter marks are also referred to as waviness or waves in this thesis because the cutter marks are in shape of waves and they account for waviness components in the whole spectra of surface analysis.

The formation and the patterns of these cutter marks are primarily dependent upon the feed speed, the cutterhead rotary speed and the number of finishing cutting edges on
the cutterhead. The relationship among these parameters, as expressed in Eq. 1-1, is well established and widely used.

\[
p = \frac{V}{N \cdot n}
\]

Eq. 1-1

where

\[
p = \text{cutter mark pitch (mm)}
\]

\[V = \text{workpiece feed speed (mm/mm)}
\]

\[N = \text{number of cutting edges}
\]

\[n = \text{angular velocity of the cutter head (rev/min)}
\]

While the underlying kinematics of the rotary machining process is a trochoid\(^1\), the cutter marks are normally approximated to be circular arcs, as shown in Fig. 1-4.

In Fig. 1-4, \(w\) is the width of cutter marks measured between neighboring cusps of cutter marks, in contrast to \(p\) being the pitch of cutter marks measured between neighboring valleys of cutter marks. Ideally, \(w\) and \(p\) should be identical in measurement. In reality, however, these two are seldom equal due to cutter mark defects, which will be discussed later.

The cutter mark height is approximately described as follows:

\[
h = R - \sqrt{R^2 - \frac{w^2}{4}}
\]

Eq. 1-2

where \(R\) is the effective cutting radius.

---

\(^1\) More information about trochoid and cutter tip's locus in rotary machining process can be found in Appendix A
A good quality surface is classified by a wave pitch of typically < 1.5 mm, and lower quality surface by a wave pitch of typically > 2.5 mm [3]. When a cutting radius of 63 mm is used, the wave heights will be < 4.5 μm for the high quality surface and > 12.4 μm for the lower quality surface.

In Fig. 1-4, every cutter mark wave seems equal in width and height. Actually, that is seldom the case. The width and the height of cutter marks are normally varying, and the variation occurs in a certain pattern, which is influenced by proud knife and spindle vibration. Proud knife is the knife on a cutterhead that has the largest effective cutting radius and therefore determines the final cutter mark pattern. Spindle vibration causes effective cutting radius to change periodically. So a typical cutter mark pattern may look like those in Fig. 1-5. (a) in Fig. 1-5 shows a cutter mark pattern produced by 4 knives per revolution with one proud. The centres of the cutting circles are at the same high level, but the proud knife has a larger cutting radius \( R_p \) than others. (b) in Fig. 1-5 shows a cutter mark pattern produced by 4 knives per revolution with spindle vertical vibration. In this case, the cutting radii do not change, but the centres of the cutting circles moves up and down periodically. (a) and (b) in Fig. 1-5 are two idealized situations. The actual cutter mark pattern can be combination of these two types and maybe some other types. More studies about cutter mark patterns and simulation of various types of cutter mark patterns are referred to [1, 4, 5].

![Diagram of cutter mark patterns](image)

(a) 4 knives per revolution with one proud

(b) 4 knives per revolution with spindle vertical vibration

Fig. 1-5 Cutter mark patterns
The cutter mark width and the cutter mark height are more intuitive than the pitch in terms of assessment of cutter marks, as cusps of cutter marks are easier to mark out than valleys of cutter marks. Between the width and the height, the width is more intuitive, because the width is in order of millimetres, while the height is in order of micrometers.

The cutter mark width and the cutter mark height are important indicators for assessment of surface quality of machined wood products. In general, the smaller the width and the height, the better the surface quality. Due to the kinematics of the rotary machining process, however, cutter marks on machined wood surfaces cannot be eliminated completely with conventional planers and moulders. In fact, wood surfaces are normally aesthetically assessed as in furniture industry. So these cutter marks are not necessarily defects in themselves provided they are even in widths and heights. However, due to a variety of reasons, such as different effective rotating radii of knives on a cutterhead, cutterhead oscillations, weak structures of machines, and so on, the cutter marks, normally have different widths and heights from each other, which could sometimes be discerned by human eyes, thereby reducing the aesthetic value of the product. The variation of cutter marks of this kind is regarded as waviness defects in the wood working industry, and can be described by the following indicators [1]:

\[
R_w = \frac{w_{\text{min}}}{w_{\text{max}}}
\]

Eq. 1-3

where

\[ w_{\text{min}} = \text{minimum wave width} \]
\[ w_{\text{max}} = \text{maximum wave width} \]

and

\[
R_h = \frac{h_{\text{min}}}{h_{\text{max}}}
\]

Eq. 1-4

where

\[ h_{\text{min}} = \text{minimum wave height} \]
\[ h_{\text{max}} = \text{maximum wave height} \]

\[ ^2 \text{Cutter marks can be eliminated completely in theory with a real-time controlled cutting spindle as described in [5]} \]
1.3 Surface of machined wood products

First of all, it must be made clear that the phrase 'machined wood products' or 'machined wood surfaces' in this thesis solely means planed wood products or surfaces. Other machining processes employed in the woodworking industry such as sanding are not included in the scope of the research.

Machined wood surfaces have quite different characteristics from machined metal surfaces. Generally speaking, machined wood surfaces are coarser than machined metal surfaces due to biological natures of wood such as pores on the wood surface, which are cross-sections of canals embedded in wood. In addition, wood surfaces are more subject to ambient temperature and humidity. It is common sense that a piece of wood may warp or twist over time.

In order to describe and analyse machined wood surfaces, wood surface irregularities, are classified into five orders [1]:

- The first order: Irregularities such as error of form, e.g. bow or twist
- The second order: Irregularities caused by malfunction of the machine, e.g. waviness variation
- The third order: Irregularities which would be present on a perfect workpiece produced on a perfect machine, e.g. cutter marks
- The fourth order: Irregularities due to the cutting process itself, e.g. chipped grain, raised grain, and fuzzy grain
- The fifth order: Irregularities due to the inherent texture, often called primary texture, e.g. grain texture

The fifth order of irregularities is caused by the microscopic pores and canals, which form during the growth of the tree. The size of the pores and canals can be of the order of 200 μm [6]. Irregularities of this type are the fundamental components on a wood surface. From a metrology point of view, these irregularities account for surface roughness.

Irregularities of the fourth order are defects by all means, which are caused by the combination of improper wood conditions such as humidity and improper cutting conditions such as worn cutting edges. Study of irregularities of this type is not in the scope of this thesis.
The second and the third order of irregularities are regarding cutter marks. Irregularities of the third order are not defects, as they are produced anyway in theory; while irregularities of the second order are defects. Since cutter marks account for surface waviness from a metrology point of view, irregularities of the second order are known as waviness defects. Measurement and description of cutter marks is the main subject in this thesis.

Different from metal surfaces, on which waviness normally has larger amplitudes than roughness, roughness on machined wood surfaces can have larger amplitudes than waviness. This is due to microscopic characteristics of wood structures. Roughness on machined wood surfaces is not only determined by the machining processes, but also by the anatomical features of wood, such as pores and canals, which can have larger influence on the finish. In [1], it is reported that the amplitude of primary texture, i.e., surface roughness, can be up to 200 μm. For high quality wood products, waviness amplitudes of less than 10 μm are not unusual. As a result, roughness on machined wood surfaces is larger than waviness in amplitude.

Furthermore, there is another difference of machined wood surfaces from machined metal surfaces due to the microscopic characteristics of wood. On machined metal surfaces, there is normally a distinct texture pattern known as lay. When there is a parallel texture pattern (parallel lay or perpendicular lay) on the surface, traces taken in parallel at right angles to the lay will be very similar. As a result, a single trace taken at right angles to the lay is usually regarded as a representation of the entire surface in most of metal surface measurement. However, due to the fact that the microscopic characteristics on machined wood surfaces distribute in a less regular manner, if not entirely random, and these characteristics normally have larger influence than machining on the surface, even though cutter marks can be seen as lay, traces taken at different locations are very likely to differ remarkably. This will be further discussed in Chapter 4.

The first order of irregularities is long wavelength components in surface analysis, which account for form of a surface. Irregularities of this type are basically caused by improper fixture during machining, or more likely, naturally deformation over time. In [1], amplitude of 0.025 mm in a 25 mm long sample is presented as an example. Measuring irregularities of this type are not in the scope of the thesis generally, although some care is taken to eliminate form from the surface before further analysis is to be conducted.
In summary, a machined wood surface is a combination of irregularities of various orders.

1.4 Inspection of surface quality of machined wood products

As other modern industries, the woodworking industry is driven by efficiency and quality. With the cutting speed and the feed speed generally increasing, it becomes highly desirable to be able to inspect cutter mark defects in-process, for delayed discovery of problems could mean a large amount of waste. In addition, cutter marks are principally signatures left behind on the wood surface by the cutting machine via the cutters. Therefore, by interpreting the cutter mark patterns, machining conditions, such as cutting edge wear, proud knives, and vibration of the cutterhead and the machine etc, can be monitored. Monitoring these conditions is critical in maintenance management. This also makes in-process inspection of cutter marks highly desirable in the woodworking industry.

Compared to surface inspection in the metal industry, surface inspection in the wood industry has been attracting less attention from both industrial and academic sectors. Nevertheless, the efforts made for inspection of wood surface quality can still be tracked back to half a century ago. Previous researchers have studied from primitive methods such as visual and tactile methods to the latest optical and machine vision techniques. The most investigated methods are:

- Stylus tracing method
- Triangulation sensing method
- Shadow analysis method
- Light Sectioning method

All these methods will be discussed in Chapter 2 of this thesis.

1.5 Scope of the research

This research is aimed at investigating methods that can potentially be used in inspection of surface quality of machined wood products in terms of cutter marks or surface waviness.

In generic surface metrology, surface measurement results in a statistic number or a set of statistic numbers, which indicate the surface roughness or waviness, such as $R_a$, $R_q$ etc. The purpose of surface measurement of this kind is to assess the surface if it has been machined up to a certain level of quality or if it satisfies requirements for a certain
function. In this case, the area that is measured is just a sample of the surface, which is believed to be able to represent the whole surface.

The purpose of measuring machined wood surfaces investigated in this thesis is not to look for a statistic number or a set of statistic numbers, but to continuously trace the cutter marks on the surface so that the surface quality and machining conditions can be monitored in a continuous manner while the machining process is ongoing.

The methods investigated in this research are supposed to be able to work in process, i.e., work on fast moving workpiece. However, as the first step towards the final objective, static samples are used in investigating the methods, which are devised with moving samples in mind.

1.6 Outline of the thesis

After this introduction chapter, a thorough literature review is presented in Chapter 2, where various relevant previous researches are described and discussed.

The construction of the test rig and descriptions of components of the rig are presented in Chapter 3. On the whole, the test rig is an imaging system. However, since several methods are investigated in this research, the test rig has to be configured in different ways for different methods.

In Chapter 4, measurement of machined wood surfaces with a laser profilometer is described and discussed. This laser profilometer will be used as a reference for the methods that will be discussed in the following chapters.

The first method investigated in this research is the Light Sectioning method. Although the Light Sectioning method has been studied in the past, the investigation reported in Chapter 5 is an innovative effort to apply up-to-date machine vision technology to the Light Sectioning method.

In Chapter 6, the Shadow Analysis method is discussed. The discussion starts with an improvement to a previous research reported in [2, 7], and then a novel approach, multi-angle Shadow Analysis method, is proposed.

In Chapter 7, the Photometric Stereo method is proposed and tested. This method is based on a surface reflection model known as Lambertian model. Experimental results
indicate that the Photometric Stereo method is very promising. In Chapter 7, the Shape From Shading method is also discussed.

In Chapter 8, surface profiles measured from 9 samples with the laser profilometer, the Light Sectioning method, the Photometric Stereo method and the Shape From Shading method respectively are compared. Due to the fact that the Shadow Analysis method is not able to give surface profiles, the Shadow Analysis method is not compared in this chapter.

Finally, conclusions are made in Chapter 9, and future work that may be conducted in the future research is suggested in Chapter 10.
2. Literature review

In this chapter, the methods for measuring machined wood surfaces are reviewed. For the sake of open-mindedness, the methods reviewed include not only the methods for measuring cutter mark waves on wood, which actually are rare, but also those for measuring surface roughness. Similarly, the review is not just restricted to wood surfaces, but at some point extended to metal surfaces. Even some research on range finding is included in the review. The methods reviewed in this chapter are organised in the categories as follows:

- Stylus tracing technique
- Optical tracing technique
- Shadow analysis method
- Light Sectioning method
- Other methods

2.1 Stylus tracing technique

Stylus tracing is the most widely used technique in surface metrology. This technique is primarily developed for measurement of machined metal surfaces. There have been various commercial stylus tracers available on the market, such as Talysurf and Talyrond from Taylor Hobson Ltd. When people became interested in measuring machined wood surfaces, the stylus tracing technique was naturally adopted with some considerations specific to wood surfaces.

2.1.1 Principles

The principle of stylus tracing technique is to run a stylus across the measured surface to produce a 2-dimensional profile of the surface, from which surface parameters such as Ra (Roughness Average) and Wa (Waviness Average) can be statistically calculated. Fig. 2-1 illustrates a typical configuration of stylus tracing instruments. Clearly, stylus tracing is a contact technique, which requires the stylus tip to touch and follow the measured surface. In addition, stylus tracing instruments can merely trace a 2-D profile in each measurement. Stylus tracing is a mature technique. The design and usage of stylus tracers have been standardized by the ISO.
2.1.2 Concerns with using stylus tracing instruments

It is easy to assume that a stylus tracing instrument always produces a reliable and accurate representation of the surface. However, this is only based on an assumption that the stylus tip can on the one hand precisely follow the variation of the surface height, and on the other hand would not deform the surface. Actually, this is both impossible and unnecessary. There are some concerns in designing or using a stylus tracer.

2.1.2.1 Tip size and geometrical shape of the stylus

Any stylus has a certain tip size and a geometrical shape, which will inevitably introduce some errors. Fig. 2-2 illustrates some types of errors introduced by a spherical stylus. Clearly, the larger the spherical stylus is, the greater the errors could be. However, a smaller stylus tip tends to pick up finer details, which may not be useful. Therefore, the geometrical shape and size of a stylus tip are important factors affecting its performance.
As indicated in Chapter 1, a surface profile can be regarded as a combination of various texture components with different amplitude and wavelengths. No matter whether evaluating surface roughness or surface waviness is concerned, the operator normally only wants to know the information of interest and does not want the stylus to pick up too much irrelevant information. In fact, the stylus tip acts as a mechanical low pass filter, whose filtering characteristics are determined by its geometrical shape and dimensions. Normally, the smaller the tip size is, the finer details of the surface can be picked up, and therefore higher frequencies and short wavelengths of surface texture components will be traced. Also the smaller the stylus tip is, the larger the pressure worked on the measured surface, which could cause more deformation errors.

According to BS EN ISO 3274:1998, the ideal stylus shape is a cone with a spherical tip. The nominal tip radius are 2, 5, or 10 μm, and the cone angles are 60° and 90° [9].

More discussion on effects of stylus radius on the roughness measurement with stylus tracers can be found in [10] and [11].

2.1.2.2 Measuring force

The measuring force is defined by BS EN ISO 3274:1998 as the force exerted by the stylus tip when in its mean position as it rests on the surface [9]. The force is for ensuring a solid contact between the stylus tip and the measured surface. The standard recommends the force to be 0.00075N. Again, this is supposed to be recommended for metal surfaces.

A stylus is normally made of metal, and even bonded with a diamond tip. In comparison, wood is always softer than the stylus tip. Consequently, if the stylus is pressed too hard onto the surface, it will ‘cut into’ the surface that it is measuring. This will inevitably cause measuring errors along with damaging the surface. On the other hand, however, if the stylus is pressed with too small a force, the tip may not be able to follow the surface profile precisely because of friction between the stylus and its holder, and friction between the stylus and the surface as well.

Apart from the above factors, the stylus holder arm deformations and lateral arm deflections due to improper measuring force can also result in measuring errors [12].
2.1.2.3 Measuring speed

The stylus cannot traverse too fast across the surface in order to avoid bouncing. The stylus and the mechanism that keeps the stylus touching the surface is a typical spring-friction system, which is inclined to vibrate when the traverse speed goes beyond a certain threshold. This limitation applies to the stylus tracing technique generally, no matter what surfaces are involved. This makes the stylus tracing technique only suitable for slow measurement.

2.1.3 Previous work

Quite a few researchers have investigated the feasibility of stylus tracing technique for wood surfaces and analysed its performance. Elmendorf and Vaughan [6] used metal surface tracers, Talysurf and Forster, to measure wood surface roughness and waviness. The Forster instrument, made by Ernst Leitz GmbH, employs a unique stylus, known as oscillating stylus, which measures the surface at discrete points, rather than in a continuous way. Besides, the Forster instrument records surface profiles on films through an optical system. The Forster instrument has a cone-shaped stylus with a tip of 0.055 mm in radius; while the Talysurf instrument has the form of a four-sided 90° diamond pyramid with a roughly 0.002 mm wide tip. Elmendorf and Vaughan also compared profiles measured with these two instruments at the same conditions, and they found that a ratio of vertical to horizontal magnification of 10:1 produced the best results.

Hann and Goodchild developed stylus tracing devices to measure wood surface waviness. Hann used a larger radius stylus of 3 mm to filter out the effects of primary texture [13], while Goodchild employed a 0.050 mm radius stylus [14]. They both obtained good waviness assessment. Nevertheless, Goodchild reported that a secondary texture defect known as chipped grain was also picked up by the stylus. This may be due to a relative small stylus tip used by Goodchild.

Peters and Cumming [15] in their research investigated almost all aspects of stylus tracing technique for wood surfaces, from stylus tip geometry to deformation of the surface caused by the force worked by the stylus on the surface and the friction between the stylus and the surface, from effects on measurements of various types of reference planes to selecting transducers. They concluded that a direct displacement type transducer with follower-skids and a low-mass stylus were best suitable for wood surface.
measurements, and that possibly more than one stylus tip size would be required to cover broad range of surfaces [15].

Peters and Mergen [16] developed a stylus-tracing device, which had a stylus of 0.001 inch (0.0254 mm) in radius and 1.5 grams in weight. The maximum measurement depth was 0.250 inch (6.35 mm), and the measurement resolution was 0.0001 inch (0.00254 mm). The tracing speed was 3 inches per minute (76.2 mm/min), and tracing length was 2 inches (50.8 mm) minimum, and two parallel 4-inch-long (101.6 mm) dull knife skids were used to form a reference plane.

Jackson [1] tried with Talylm, Talyrond, and Talysurf to measure steel samples and wood samples with different tips, and concluded that these metal surface tracers were not suitable for wood surface measurement. The main shortcomings of metal surface tracers are

- Due to the small stylus tip, the primary filtration cannot be achieved, and secondary filtration through electronic circuitry or computer algorithms does not provide a satisfactory effect
- It is difficult to achieve a good balance between horizontal magnifications and vertical magnifications.
- The reference skid, if available, is too short to allow accurate peak to valley height recording of the longer wavelength effects.
- No instrument has taken into account the errors of form (bow or twist), which result in the problem of ‘over range’.

Furthermore, Jackson developed a measuring device specific for wood surface waviness, called Waviness Recording Instrument (WRI). In the device, a 5 mm diameter \( \times \) 5 mm long roller was used as the stylus and the measuring force was 90 gm. In addition, a skid length of 50 mm was chosen to provide an adequate reference plane for cutter mark waves with longer wavelengths. It is noted that the size of the stylus and the measuring force are fairly large compared to other research. The larger stylus succeeded in filtering out the primary texture of the surface, thus resulting in excellent surface tracing in terms of cutter mark waves. However, due to a relatively high contact force (90 gm), the stylus compresses the peaks of the surface waves, thus producing a reduced height profile trace. Hence, Jackson believes that the WRI instrument is not suitable for absolute measurement of wave heights of cutter marks [3].
2.1.4 Conclusion

According to the research mentioned above, the stylus tracing technique can be used in measuring wood surfaces to some extent. Due to the advantages of simple and cheap configuration, high reliability and potentially high measuring accuracy [17], stylus tracing technique has been widely used for surface measurement both in metal working industry and wood working industry. The results from this technique are always compared to results from other techniques as a reference.

However, this technique has some drawbacks. Due to being a contact technique, improper measuring force may not only introduce errors but also scratch the surface being measured. Moreover, the measuring speed of this technique is too slow compared to other more advanced techniques. Clearly, such a contact technique is not suitable for in-process measurement.

2.2 Optical tracing technique

The stylus tracing technique discussed in the last section always employs a mechanical stylus. With the development of sensing technology, optical sensors are integrated into tracing instruments, which are referred to as optical tracing technique in this thesis.

Different from the stylus tracing technique, the optical tracing technique normally employs optical sensors rather than mechanical stylus, although the optical sensor is referred to as light stylus in some literature. Due to the non-contact nature and high data rate inherent with optical sensors, the measuring speed of optical tracers is much higher than stylus tracers. Also due to non-contact nature, the concerns with the measuring force and the consequent deform errors do not apply in optical tracing technique. In addition, there is no probe wear to concern. The problem of the tip size in the optical tracing technique becomes the problem of light spot size, or laser spot size, for laser is always used as the light source. Normally, the laser spot size is very small, down to a few micrometers.

Similar to the stylus tracer, the optical tracer also requires scanning to produce a surface profile, and the resultant profile is also a 2-D profile. Although the optical tracer normally has a high data rate, when many profiles are to be traced by scanning, it can still be time-consuming to measure a surface. This is actually associated with a question...
single profile good enough to represent a surface, or more specifically, a wood surface? This question will be discussed in the following chapters, especially in Chapter 4.

In this section, two types of optical tracers will be discussed. They both use laser as the light source, but they use the laser in different ways. One type is based on a technique known as auto-focusing, while the other based on triangulation sensing.

2.2.1 Auto-focusing optical sensor

The principle of the auto-focusing sensor is illustrated in Fig. 2-3. As shown in the figure, the laser light goes through a beam splitter and a collimator, and then is focused on the surface, from which the laser light is reflected. The reflected light goes through the same optical path but in an opposite direction until the beam splitter, where the reflected light is diverted to a focus detector. The focus detector evaluates the degree of focus. When the initial focus is lost due to the relative movement of the surface, a servo mechanism will drive the lens accordingly to make the laser spot focused again. The displacement of the focusing lens is recorded by a displacement sensor, which actually records the surface height variations.

In [18], an auto-focusing tracer is used to measure 3-D surface roughness on wood surfaces. After data having been collected with the tracer from a wood surface, special software is run to count the peaks and valleys, from which surface roughness parameters are calculated. In [19], an optical sensor based on the auto-focusing principle is developed to measure roundness.

In this research, an auto-focusing optical tracer, referred to as laser profilometer in Chapter 4 and the following chapters, is used to measure wood surfaces. Surface profiles measured with the laser profilometer will act as references for other methods investigated in this research.
2.2.2 Laser displacement sensor

The principle of the laser displacement sensor (LDS), also known as triangulation sensor, is illustrated in Fig. 2-4. As shown in the figure, light projected by the laser is focused onto the surface to be measured, and the scattered light from the surface is then collected by an imaging lens onto the detector. When the surface is at height $h_1$, the imaged laser spot is at position $p_1$ on the detector; when the surface changes to height $h_2$, the corresponding spot image changes to $p_2$ on the detector. Essentially, the surface height variations are converted to the change of lateral positions of the imaged laser spot on the detector.
The detector in a laser displacement sensor can be a position sensitive detector (PSD) or a charge coupled device (CCD). The difference between the two types is that the PSD is based on analogue technology, while the CCD is a digital device. Both the PSD and the CCD have advantages and disadvantages.

The biggest advantage of the PSD is the very high data rate, which can be up to 200 kHz or faster [20]. Moreover, the gain control of the PSD can be made very fast, which gives the PSD very good dynamic light reception capability. The resolution of the PSD can be very high, in principle only limited by the signal conditioning circuitry. The disadvantages of the PSD are lack of ability to deal with multiple light spots and lack of ability to display an image or profile of the detector pattern. However, if only considering wood surface measurement, these disadvantages are not critical.

The biggest advantage of the CCD over the PSD is that the output of the sensor can be displayed on a screen to evaluate the light levels, cleanliness of the image, and if there are stray light effects, and accordingly processed to remove unwanted multiple spots and reflections or stray light. The CCD is the core of digital cameras. In some research [17], the CCD is replaced with a CCD camera, along with a separate laser as light source.

Compared to the PSD, the CCD has lower data rates, and narrow dynamic range. In the past, the CCD was criticized with poor position resolution and requirement that the laser spot be smaller than the pixel. However, all these are changing with the development of the CCD technology. Sandak considers the CCD an attractive alternative to the PSD, even superior to the PSD in some aspects [21].

Compared to auto-focusing sensors, the laser displacement sensor has much larger standoff, i.e. the distance between the sensor and the surface. The standoff for the auto-focusing tracer used in this research is only about 1 mm. In contrast, the standoff for laser displacement sensors can be from 10 mm up to more than 1000 mm, depending on the resolution required. A large standoff is an advantage in some cases, such as the object to be measured having large vibration amplitude.

2.2.3 Previous work

2.2.3.1 Work done by Funck et al

Funck et al [17] developed a laser scatter/optical imaging system to measure veneer surface roughness, and compared the results from the system to those from a conventional
A 1.0 mW helium neon laser is placed 375 mm perpendicular to the veneer surface. The laser beam passes through a 49 mm polarizing filter and then a pinhole aperture approximately 100 μm in diameter. This results in a laser dot with a diameter of approximately 3 mm on the veneer surface. Light reflected from the sample surface is captured by a CCD video camera mounted at an angle of 19° to the sample surface.

A spatial resolution of 675 pixels per inch of vertical displacement is obtained with the above configuration, i.e., each pixel change in laser dot’s centroid position representing 0.038 mm (0.0015 inch) change in surface height [17].

The profile obtained with the laser scatter/optical imaging system and that obtained with a conventional stylus tracer were in good accordance, except the laser system slightly smoothed the data compared to the stylus device [17]. The reason for that given by Funck et al. is that compared to the size of the stylus tip 12.5 microns, the size of the laser dot 3 mm on the surface is relatively large, which acts as a low-pass filter, attenuating the high frequency components of the surface profile.
2.2.3.2 Work done by Yoo et al

Yoo et al [ used a laser detector system (LDS\textsuperscript{3}) to measure the roughness on wood surfaces. A schematic diagram of the system is shown in Fig. 2-6. As shown in the figure, a laser beam is projected onto the surface, and then reflected into a detector, which is a PSD. The paper [12] does not mention if there is a lens to collect the reflection from the surface. The laser detector system is essentially based on triangulation sensing method.

![Schematic of a laser detector system](image)

Fig. 2-6 Schematic of a laser detector system in [12]

Yoo et al used the laser detector system to measure roughness profiles of wood specimens. The paper does not indicate what type of instrument was used as a reference for the measurements done with the LDS. However, comparison shows that the roughness profiles measured with the LDS are in good agreement with the actual profiles.

2.2.3.3 Work done by Lemaster et al

Lemaster et al have conducted comprehensive studies on optical profilometers suitable for field use on woodworking machinery [22-31]. The principle of the optical profilometers Lemaster et al have studied is the same as the LDS: the positional change of the reflected laser spot on the surface of the detector is correlated to the vertical height change of the workpiece. By moving the workpiece beneath the detector and recording the change in the position of the laser spot, a two-dimensional surface profile is obtained. Lemaster et al compared the surface profile obtained with the profilometers to that

\textsuperscript{3} LDS always stands for Laser Displacement Sensor in this thesis except this one.
obtained with the traditional stylus system, and found that the profiles were very similar to each other.

Lemaster et al have developed such profilometers in two versions. a laboratory-based system and a commercial laser sensor system. The laboratory-based system consists of a camera and a laser, similar to Funck's research. The commercial laser sensor system integrates a light source and a photodetector in a single housing. In [29], Lemaster mentioned a commercially available sensor with a laser spot size of 150x250 µm, which is larger than typical laser spot sizes (50 µm in diameter). According to [29], the large laser spot yielded satisfactory results for waviness and some larger roughness surface irregularities, but could not distinguish between fine roughness details such as those found on surfaces sanded with fine grit sandpaper. This is understandable because laser spots serve a function of low-pass filtering and a larger spot size makes the cut-off frequency lower.

2.2.3.4 Work done by Sandak et al

The latest research on using laser displacement sensor to measure wood surfaces was done by Sandak et al [21, 32]. In [32], effects of wood species on evaluation of surface smoothness by laser displacement sensor were investigated. Special triangular profiles were carefully made on 15 wood species with different densities and colors. Profiles of these specimens were measured with a laser displacement sensor. The LDS profiles were compared to profiles measured with a stylus tracer. Experimental results show that the LDS profiles are good reproduction of the actual profiles in general, especially in case of medium darkness and medium density wood specimens. However, the LDS accuracy depends on the wood properties such as density and color, installation position of the sensor, and profile shape. There are some conclusions made by Sandak [32]:

- All laser-scanned lines tend round off profile valleys and peaks.
- Roughness parameters calculated from laser profiles differ slightly when different wood species are scanned There is a need to evaluate some corrections of surface roughness descriptors calculated from laser-scanned profiles.
- Laser displacement sensor accuracy decreases gradually when the specific density of the wood changes from medium to low or high.
• Evaluation of very dark or very bright surface profiles is limited because of the LDS's tendency to generate high-frequency noise.

In addition, Sandak indicates that a laser displacement sensor installed parallel to the movement direction of the wood specimen tends to deform the real profile, i.e., the stylus profile. Accordingly, Sandak suggests the LDS be installed perpendicular to the movement direction.

In [21], two types of laser displacement sensors, a position sensitive detector (PSD) and a charge coupled device (CCD) detector, were compared with a conventional stylus and with theoretical profiles. Hornbeam workpieces with triangular profiles of differing slope and height were used for the evaluation. The profiles were made with 75, 250, and 750 μm respectively in height and with inclination angles of 45°, 30°, and 15° respectively.

The results show that accuracy of both sensors decreases as the height of the profile decreases. The error ratio of the laser-scanned profiles changes as a function of profile height, in the range 5%–33%. All laser-scanned lines have round profile valleys and peaks. Roughness estimated by laser methods falls in the range ±5% of the real roughness in the best case. In the worst cases, the error can be more than one-third of the actual value.

All profiles are generally imitated properly, especially when high profiles are scanned. With low profiles, results using the CCD sensor are closer to the theoretical profile than to those produced by PSD. Frequency analysis shows that all sensors detect the main frequency, but the magnitude of the maximum frequency components calculated from the CCD sensor profiles is closer to the corresponding stylus magnitude than does the PSD. Finally, Sandak concludes that the CCD sensor is superior to the PSD for accurate surface roughness evaluation, although the PSD can still be used for monitoring the error of form in most applications.

2.2.3.5 Work done in non-woodworking industry

The laser displacement sensor has also been employed in inspection of machined metal surfaces. Mitsui [33] developed an in-process sensor for metal surface roughness. The principle of Mitsui's sensor is shown in Fig. 2-7. Very similar to the principle shown in Fig. 2-4, the surface height variation due to the surface traverse movement will reflect incident light beam onto a screen at different positions. The screen is a photoelectric
diode array set with 256 elements. The only difference is that the reflected beam is to be captured at an angle equal to the angle of the incident beam. This is due to the reflection from metal surfaces are highly specular. Results obtained with this sensor are in good agreement with results obtained with a mechanical profilometer.

![Diagram of Mitsui's sensor](image)

**Fig. 2-7 Principle of Mitsui's sensor [33]**

Docchio *et al* [34] and Tomassini *et al* [35, 36] also developed an optical sensor to measure surface roughness and waviness on metal samples. The sensor, as illustrated in Fig. 2-8, consists of two parts: one part is actually a commercial triangulation sensor with dual PSDs, referred to as triangulator in [34], which produces two signals denoted as $T_d$ and $S_{c1}$. The signal $T_d$ is a positional signal proportional to the distance between the sensor and the target surface, while the signal $S_{c1}$ is an intensity signal proportional to the intensity of the light scattered at an angle $\theta_1 = 43^\circ$, the other part of the sensor is a specifically designed scattering sensor head, which consists of two photodiodes placed close to the laser beam, and collects the light scattered at an angle $\theta_s = 3.8^\circ$ and produces a signal $S_{c2}$ proportional to its intensity.

Note that the triangulation sensor involved here is different from the triangulation sensor discussed earlier on in that this triangulation sensor can not only produce positional signals, but also intensity signals.
The signals from the sensor are processed as illustrated in Fig 2-9. The roughness and waviness are processed through different channels. The waviness information is derived by processing the triangulator distance signal $T_d$, which is first bandpass filtered to remove the form factor and the roughness components, then processed using the Fast Fourier Transform (FFT). The FFT output contains information about the spatial wavelength and the amplitude of possible waviness. The determination of the roughness parameter is obtained by a combination of signals $S_1$ and $S_2$ with the high frequency components of signal $T_d$. The measuring range of the sensor is $1 \text{mm} - 100 \text{mm}$ for waviness and $0.1 - 1 \mu m$.

In addition to the above two researches, another researcher Costa developed a series of triangulation-based surface inspection systems to map the surface topography [37]. The core of the inspection systems is a triangulation sensor. Costa’s inspection systems are used for thickness measurement, relief mapping of different kinds of films (polyethylene, thin sputter copper, tin dioxide and silver films) and several kinds of fabrics, and
roughness measurement and topographic inspection of polyethylene moulds and graphite samples. Costa’s research proves that the triangulation sensor works with surfaces of a variety of materials, although wood is not mentioned.

2.2.4 Conclusions

Previous studies have proven that the laser displacement sensor, or termed as the triangulation sensor, is a good choice to evaluate surface roughness, including wood surface roughness, especially in online applications. The only question is how well the LDS can reproduce the surface profile. All the previous studies discussed above claim a good comparison between the LDS profiles and reference profiles. Evaluating roughness and evaluating waviness do not have much difference in principle. The waviness profile can be extracted from the primary profile by removal of roughness information. Therefore, it is reasonable to assume that a well-selected laser displacement sensor will be able to evaluate wood waviness profiles, i.e. cutter mark wave profiles.

In conclusion, laser displacement sensors are effective tools for measuring surface roughness and waviness, and there are commercial triangulation sensors available. However, the laser displacement sensor, similar to the stylus tracer, can only produce a single surface profile in each scan, which may misrepresent the actual surface as a whole. The misrepresentation of the actual surface by a single profile can be seen in Chapter 4. Although this problem may be overcome by averaging multiple surface profiles, this approach is not easy to be implemented in an online system, especially when dozens of profiles are needed. From this point of view, a measurement based on an area is better than that based on a single profile, or a few profiles. This is why the next method seems better.

2.3 Shadow analysis method

2.3.1 Principles

The basic idea of the Shadow Analysis method is to direct light at a small oblique angle to the surface in the feed direction\(^4\), thus areas on the surface towards the light being illuminated and therefore bright, and areas opposite to the light being in shadows and hence dark. Fig. 2-10 is an illustration of oblique illumination and its effects on the

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\(^4\) i.e. the feed direction when the sample is being machined
surface. Fig. 2-11 is an image taken from a wood surface under oblique illumination. As seen in Fig. 2-10, the periodic variation of bright and dark areas on the surface reflects the variation of surface heights. The theoretical imitation is reflected in the image shown in Fig. 2-11. The cutter mark waves, i.e. surface height variations, are clear in the image.

The Shadow Analysis method is not always implemented in the same way. Under the same or similar illumination scheme as shown in Fig 2-10, different image processing approaches may be employed. Therefore, the Shadow Analysis method is actually a collective term for all the methods for deriving surface information from shadows on the surface.

Fig. 2-10 Oblique illumination and shadows
2.3.2 Previous work

There have been some investigations on assessment of wood surface roughness or waviness by analysis of shadows on the obliquely illuminated surface, the primary difference among the approaches employed in these investigations is how to infer the roughness or waviness from the image of the obliquely illuminated surface.

2.3.2.1 Work done by Elmendorf and Vaughan

In Elmendorf and Vaughan’s research [6], the Shadow Analysis method is termed as ‘highlighting test’. In one of Elmendorf and Vaughan’s experiments, a source of light is placed at an acute angle to a sanded wood surface, so that the light streams across the grain. By photographing the surface from above with a sharp focus, it becomes possible to photograph very small ridges and depressions in the surface of the wood [6]. It is reported by Elmendorf and Vaughan that a good camera could pick up grooves cut by 4/0 sandpaper. In another Elmendorf and Vaughan’s experiment, light is directed in the direction of wood grain instead of across grain, and the photographs are taken through a microscope. Although clear images are obtained in both experiments, these images are only qualitatively used to ‘highlight’ the difference that microseal process could do. Interestingly, in [6], a ‘shadow test’ is mentioned, but the test is designed for showing the
effects of microsealing on coated surfaces, and it has nothing to do with the Shadow Analysis method discussed here.

2.3.2.2 Work done by Faust and Zhao

Faust employed a Shadow Analysis method in [38] to measure veneer surface roughness by image analysis. In Faust’s experiment, a common slide projector was used to provide a source of collimated light that produced sharp, clear shadowing on the veneer surface. Faust believed that the intensity of the light was high enough to ‘washout’ the darker features on the wood surface such as latewood bands, pitch streaks, and other wood defects. A critical parameter in Faust’s experiment is the angle of incidence, which was determined by a series of experiments. According to Faust, the optimum angle of incidence is 7 degrees, at which the greatest resolution in distinguishing the visually classified rough and smooth veneer surfaces is obtained.

After images had been taken of the obliquely illuminated veneer surface with a video camera, the threshold level of grey scale became another critical parameter. The threshold was determined empirically through a repeated process: enhancing the image with an arbitrary threshold level first, then visually comparing the enhanced image to roughness observed on the surface, and increasing the threshold level if the enhanced image indicated more roughness than was actually on the surface, or decreasing the threshold level if the enhanced image indicated less roughness than was actually on the surface. This process was repeated until a threshold level was found that produced an enhanced image representing the actual roughness on the surface of the veneer as determined by visual assessment.

After images were enhanced, two roughness indices were calculated, namely Frequency and DPixel. The Frequency index is a measure of the frequency of peaks and valleys as scanned perpendicular to the grain, while the DPixel index is simply a count of the dark pixels (shadows) in the enhanced video images [38]. Finally, results from this method were correlated with those from stylus tracing and visual classification. The correlation coefficient between results from image analysis and from stylus tracing was 0.88; and the correlation coefficient between results from image analysis and from visual classification was 0.99. Faust supposed that the relatively large variation between the image analysis and stylus tracing technique was probably because stylus tracing measurement was based on surface profiles, while shadow analysis was based on areas.
It is noted that in Faust’s research, only roughness indices were calculated, which Faust believed were the best indices to describe the surface roughness. But Faust did not try to obtain surface profiles, which are easily obtained by a stylus tracer.

Zhao employed the same approach as Faust to evaluate wood surface quality in [39]. Also, the optimum angle of incidence was determined by tests. Images were taken with a video camera on areas with a dimension of $50 \times 50$ mm$^2$. However, a different image analysis algorithm was taken, which had initially been developed for the classification of aerial photographic images. Three indices, namely Angular Second Moment (ASM), Contrast (CTR) and Correlation (CORR), were calculated accordingly. The resulting classification of samples using these indices was in good agreement with pre-known classification, and the overall accuracy was up to 96.5%. However, Zhao did not try to measure surface profiles either.

Essentially, both Faust’s and Zhao’s research were based on statistical analysis of images. This approach is very suitable for surface roughness, as surface roughness is always described statistically. Furthermore, surface roughness obtained from an area is supposed to be more reliable than that obtained from a single trace.

However, both Faust and Zhao focused work on wood surface roughness, and surface waviness was not studied.

2.3.2.3 Work done by Hoffmeister et al

The latest research on assessment of wood surface waviness with the Shadow Analysis method was conducted by Hoffmeister et al [2, 7]. The principle of their research is illustrated in Fig 2-12. Interestingly, although parallel rays of light are shown in the figure, the light is actually not collimated because of the diffusing screen, which makes light diffuse. Hoffmeister et al did not mention why diffuse light was selected. Actually, it is very unusual to use diffuse light other than collimated light to make shadows on the surface among relevant research.

Hoffmeister et al believe that the periodic and alternate occurrence of bright and dark regions on the obliquely illuminated surface contain the information on the cutter mark waves. Like Faust, Hoffmeister et al realise that the characteristics such as year rings and cracks etc on the wood surface may have similar grey scale values to those...
caused by shadows. But, they believe that these characteristics are distributed arbitrarily, and therefore would not influence the surface profile from a statistic point of view [2].

![Fig. 2-12 Configuration of Hoffmeister's test rig [2]](image)

In Hoffmeister's experiment, images are taken with a CCD camera from the above, and then stored and analysed in a PC. The camera is so positioned that the columns of the image are perpendicular to the feed direction. After an image is taken, an algorithm, referred to as ‘adding column by column’ in this thesis, is applied to the image, and an intensity profile along the sample surface is obtained. Widths of cutter marks are then calculated from the intensity profile. The detailed explanation of the algorithm will be given in Chapter 6.

In [7], a software package based on the method described above was presented, which had functions of converting the width in pixel to the width in millimetre. Thus, not only can surface profiles be provided with this method, but also the widths of cutter marks can be calculated. Moreover, experiments in [7] were carried out in a real working condition where the timber was machined at a feed speed up to 60 m/min.

In [2], another algorithm for image analysis was also proposed. In the algorithm, the grey scale image is first converted to a binary image by a dynamically determined threshold, and then the widths of white and black zones on the binary image are measured. Compared to the ‘adding column by column’ algorithm, this algorithm has an advantage that if the cut widths and depths are variant in the direction perpendicular to the feed direction due to an incorrect fixing or different wear of the knives, this method is able to recognise it [2]. However, Hoffmeister et al found that this method would require
intensive computation and therefore result in a lower image analysing rate, so they did not implement this idea.

2.3.2.4 Work done by Maycock et al

Maycock’s research may not look like a Shadow Analysis method at first thought. However, further studies reveal that Maycock’s research is essentially a Shadow Analysis method in an unusual form. In Maycock’s research [4, 40, 41, 42], the target surface was also obliquely illuminated. But, the illumination was only in the form of a narrow laser strip of about 10 mm wide. Instead of a video camera, a linear photodiode array was located above the surface. The output of the linear photodiode array was corresponding to the brightness of the laser strip on the sample surface. Due to the photodiode array being a linear device rather than an area-scan one, the output of the photodiode array, i.e. an intensity profile along the laser strip, was only related to a profile on the surface. The intensity profile was not a real surface profile, but a brightness profile along the laser strip. However, Maycock believed that the real surface profile must be composed of the same frequency components as the brightness profile, and therefore the real surface profile could be inferred from the intensity profile. Hence, the intensity profile was Fourier transformed into frequency domain, and spectra were obtained, in which harmonics were believed to account for waviness components at different wavelengths.

Although Maycock’s research looks so different from other shadow analysis research, since the laser light is projected onto the surface at a very small angle (<1.5°), there must be intensity variations in the reflection due to surface textures, and the intensity variations can be differentiated by the photodiode array. Therefore, Maycock’s research is essentially a shadow analysis method.

Surface results obtained with Maycock’s method were compared to those obtained with a stylus tracing instrument Talyrond 200⁵, and also compared to the surface profiles mathematically simulated with a Surface Simulation Algorithm (SSA) developed by Maycock. The comparisons are all in good agreement.

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⁵ Talyrond is an instrument for roundness measurement. However, due to its long traverse length, Talyrond was used vertically by Maycock to measure surface profiles.
2.3.3 Conclusions

Compared to the conventional stylus tracing method, the Shadow Analysis method is non-contact, compared to the optical tracing method, the Shadow Analysis method is potentially more reliable, as the method is based on areas rather than traces, except Maycock’s method. In addition, the Shadow Analysis method has potentially higher data rates, as this method does not require scanning of the surface, and a single image may very well reveal surface roughness or waviness over an area of the surface.

Furthermore, the Shadow Analysis method relies on reflection of light in principle; and reflection of light generally will not be affected too much by vibration of the surface during cutting processes. In contrast, the optical stylus tracers measure the distances between the sensor and the measured point on the surface, vibration of the surface will clearly have much influence on the measurement.

All above advantages make the Shadow Analysis method suitable to be implemented in in-process systems. However, it must be noted that although this method is referred to as the Shadow Analysis method in this thesis, it is not a conventional term. Others may prefer other terms for this method. More importantly, this term actually proves not entirely accurate in Chapter 7.

2.4 Light Sectioning method

2.4.1 Principles

The Light Sectioning method is illustrated in Fig. 2-13. A plane of light is directed onto the target surface. Suppose the surface is absolutely flat, then the intersection of the projected light and the surface will be a straight line. As shown in Fig. 2-13, however, there are cutter mark waves on the surface, therefore the intersection of the projected light and the surface will be another wavy line. The new wavy line is referred to as a light section. The relationship between the waves of cutter marks and the waves of the light section is illustrated in Fig. 2-14.
If the angle of incidence of light is \( \theta \), and the depth of a cutter mark wave is \( H \), then the depth of the corresponding wave in the light section will be \( L = H \tan \theta \). When \( \theta \) is smaller than 45 degrees, \( L \) is greater than \( H \). The smaller the angle \( \theta \), the greater the ratio of \( L/H \).

Note that both the Light Sectioning method and the Shadow Analysis method require oblique illumination. The difference between these two methods is that the Shadow Analysis method requires light to be directed parallel to the feed direction, while the Light Sectioning method requires light to be projected perpendicular to the feed direction from the side of the surface, although the light section will be parallel to the feed direction.
2.4.2 Previous research

2.4.2.1 Previous research in the wood working industry

The Light Sectioning method is not a new concept. Early in 1936 it was first devised by Schmaltz, according to [43]. In 1951, Thunell used the Light Sectioning method to study tool wear as related to surface quality of wood [43]. The principle of the Light Sectioning method used by Thunell is illustrated in Fig. 2-15.

![Fig. 2-15 Principle of Light Sectioning method used by Thunell [43]](image)

In Fig. 2-15, \( x \) represents the actual profile height, and \( y \) the profile height when observed from the above. The relationship between \( x \) and \( y \) is expressed as

\[
y = \frac{x}{\sin 35^\circ} = 1.74x \quad \text{or} \quad x = \frac{y}{1.74}.
\]

The angle between the surface and the incident beam acts as a factor of magnification, which is 1.74 (1/\( \sin 35^\circ \)) in Thunell’s experiments. The magnification is clearly not large enough when the variation of surface heights is only in the order of microns. Therefore, a microscope was used to observe the light section.

In [43], a light sectioning system devised by Swedish Forest Products Laboratory in 1951 is presented, as shown in Fig. 2-16. The system was composed of a microscope, a light source, an optical slit and an iris shutter. No detailed information about the light source is available. The optical slit was made by shimming two optically flat surfaces.

Three light section samples made at University of California, Forest Products Laboratory are also presented in [43], as shown in Fig. 2-17. No scales for the light section samples were given in [43]. However, it is mentioned that 'A sampling length of 1
mm (0.04 in.) magnified 100 times will appear as 100 mm = 4 in., and the author pointed out that ‘This sampling length is usually too small to be representative of the surface to be tested’ [43]. A sample length of 1 mm is really too small to represent the surface, but the variation of surface heights can still be clearly seen in the pictures, especially in picture (a), which was taken from an unsanded rotary cut veneer.

Fig. 2-16 Light sectioning system devised by Swedish Forest Products Laboratory [43]

In [6], Elmendorf also described a light-sectioning test, although it was termed as light ribbon test. In the test, a light ribbon came out of a projector through a machined slot, illuminated a piece of specimen tilted at a small angle with respect to the light ribbon. The sample was under a microscope. The whole setup was very much like that shown in Fig. 2-16. It is reported that wavy lines due to light sectioning on the sample surfaces could be observed with a microscope and recorded with a camera over the eyepiece of the microscope.

In early 1960s, there were already commercial instruments for obtaining light sections on the market, which comprised light source, lenses and view eyepieces in a single compact instrument. An example of such kind of instruments was shown in [44], and it was denoted as a light-sectioning microscope manufactured by Carl Zeiss Inc, Germany. Carl Zeiss Inc is still manufacturing light sectioning microscopes along with other types of microscopes now.
In [45], Lutz used the Light Sectioning method to obtain profiles from a veneer surface. In Lutz's research, a collimated plane of light was directed (parallel to the grain) to the veneer surface at a sharp angle of incidence (no exact angle was reported). Photographs were taken of the veneer directly above the area where the plane of light was striking the surface. The plane of light, from the camera's perspective, appears as a wavy line corresponding to the profile of veneer surface. The amplitude of the profile replica could be adjusted by simply changing the angle of incidence of the light plane with respect to the veneer surface. However, considering the computing and image acquisition technologies in 1952, the method was clearly too slow and tedious to be practically applied at the time.

In [38], Faust suggested that a series of planes of collimated light in parallel would result in a series of surface profiles and thereby a better estimate of the surface topography. However, no such experiment has been reported so far.

Sandak devised a new way to make light sections, which is referred to as light sectioning shadow [46]. The setup is illustrated in Fig. 2-18. Light emitted with a fixed
small angle to the surface plane by a projector (1) is directed onto the measured surface. A curtain (3) installed in the light path close to the surface creates a shadow on the measured surface. The shape of the border between bright (highly lit area) and dark (shadow area) is a profile section of the surface. The camera (4) installed over the measured surface captures an image of the border and a digital signal processor using image analysis techniques digitizes the profile section. It is reported in [46] that high accuracy of the shadow scanner was confirmed by comparison with corresponding profiles acquired by a stylus. In addition, Sandak scanned the light section shadow across an area and obtained a 3-D surface shape.

Note that there is a cylinder lens (6) used in Sandak's research. The cylindrical lens is supposed to stretch the image in the arrowed dimension but without changing the other dimension. By this way, the resolution in the arrowed dimension is greater than that in the other dimension. The benefit of this cylindrical lens is the combination of an improved depth resolution and a large field of view in the other dimension. Detailed descriptions on using a cylindrical lens to improve depth resolution in a light sectioning based inspection is referred to [47].

2.4.2.2 Previous research in metal working industry

It is reported in [48] that a Light sectioning method was applied to measure surface roughness on a sand blasted surface. In that application, a light slit was projected at 45° from one side of the sample and the image of the projected slit was taken by a CCD camera at 45° from the other side. An interpolation algorithm was developed for refining the cross section profile. The actual dimensions of the profile were obtained by
calibrating the vision system. The results by light sectioning were in good agreement with those by a stylus instrument.

Apart from measuring surface roughness or waviness, the Light Sectioning method or similar methods have been widely used in other fields, such as surface dimensional measurements. Fig. 2-19 shows a typical application of inspecting surface contour using a light-sectioning sensor [49]. As shown in the figure, light is projected onto the surface to be inspected from an oblique direction, while the sensor is positioned right opposite the projected line on the surface. Clearly, the variation of such a surface contour as shown in Fig. 2-19 is in a relatively large order in dimensions; therefore the angle between the projected light and the sensor do not need to be very large.

Sometimes, two planes of light rather than just one are projected onto the object to be inspected, which could improve the measurement resolution. Fig 2-20 shows an example of such a system, called Consight light stripe projection system, developed and used at General Motors [50]. In the system, light from two opposite sources converges on the conveyor, thus producing two opposite lines on the piston rod. Since there are two projected lines on the part’s surface, the subsequent image processing is easier than when there is only a single projected line.

![Fig. 2-19 3-D contouring the surface using light sectioning technique [49]](image-url)
Another format of light sectioning is described in [51], which is used to inspect surface quality of exterior body panels in the automotive industry. The scheme is shown in Fig. 2-21.

The surface to be inspected in this case is reflective, thus the incident light will be reflected onto a screen nearby with the information on the surface profile where the incident light strikes. However, since wood surfaces are always diffusive rather than reflective, this method is not suitable for inspecting wood surfaces.
In fact, the key point of the Light Sectioning method is projecting light from one angle and taking images from the other. Jarvis gives a more generic description of this technique [52], which is termed light stripe projection in his paper and shown in Fig. 2-22. The distortion of the line projected onto a 3-D scene provides dimensional information of the 3-D scene [50].

![Diagram of Light Sectioning method](image)

**Fig. 2-22 Striped light apparatus [52]**

### 2.4.3 Conclusions

Although the Light Sectioning method has long been investigated, it has not yet been practically used in the wood working industry. The reason might be like what Jackson points out in [1] 'it is quantitative in that measurements taken via the microscope viewer can be used to assess overall peak to valley height, but the technique is time consuming...'. But Jackson also believes 'the method is probably worthy of further investigation for wood planing and should form the basis of a future project,'
possibly using laser techniques which have shown promised and advances in image detection/analysis systems' [1]

2.5 Other methods

2.5.1 Introduction

Apart from the conventional stylus tracing techniques, the optical tracing techniques, the Light Sectioning method, and the Shadow Analysis method, some other methods or techniques have also been tested or even used for assessing wood surface roughness or waviness. These methods and techniques will be discussed in 2.5.2. After that, some optical techniques mainly for measuring metal surfaces will be discussed in 2.5.3. Because measuring surface roughness or waviness can be seen as range finding in a sense, some range finding techniques will also be discussed in 2.5.4.

2.5.2 Other methods or techniques for assessing wood surface roughness or waviness

2.5.2.1 Visual and tactile methods

Traditionally, wood surface roughness and waviness were estimated by visual and tactile methods. Even now, they are still effective methods for qualitative inspection of wood surface quality. It is indicated in [1] that the timber industry has relied on a visual method to assess machined surface waviness, which is running a wax crayon across the machined wood surface and then counting the cutter wave marks. Detection by sight is essentially the Shadow Analysis method, which requires oblique lighting to highlight the surface topography. Instead of a camera and a computer, the human eye and the human brain are the acquisition unit and processing unit. However, these two methods are neither quantitative nor repeatable.

2.5.2.2 Pneumatic, capacitance and ultrasonic techniques

The basic idea of the pneumatic technique is blowing air onto the surface via a measuring head and skirt, and the air that escaped between the surface and the skirt can be related to the surface finish. Bonac [53] applied this technique to measure machined wood surfaces in a range of 20 – 420 microns by relating roughness of the surface with roughness volume (volume between a gauge head and the rough surface). However, due
to some other practical reasons, the pneumatic technique is not generally considered to be viable as a method for assessing timber surface quality [4]

Although capacitance and ultrasonic techniques are also reported to be able to measure surface roughness [4], no practical instruments or equipment have been available, especially for timber surfaces.

2.5.3 Optical techniques for measuring metal surfaces

Many techniques investigated for assessing surface roughness are based on analysis of the reflected beam (typically laser beam). Yoo et al. classified these techniques into four categories [12]

- Measurement of reflected beam intensity
- Measurement of reflected beam positional variation
- Interferometry
- Speckle pattern analysis

Among these techniques, the second one, i.e. 'measurement of reflected beam positional variation' has been discussed in Section 2.2.2. 'Measurement of reflected beam intensity' is also mentioned in Section 2.2.2, which in some cases is used in conjunction with 'measurement of reflected beam positional variation'. As regards to the other two techniques, generally speaking, they are mainly for measuring metal or optical surfaces; therefore they are only discussed briefly in the section.

2.5.3.1 Measurement of reflected beam intensity

This technique is also termed light scattering technique. The basic idea of this technique is that when a collimated beam of light is directed onto a surface at a certain angle, it will be either scattered in all directions if the surface is rough or reflected mainly in the specular direction if the surface is relatively smooth. Hence, assessment of surface roughness can be realised by measuring the intensity of either the specular or the diffuse component of the reflected beam or both [54]. Such measurement can be realised using either photo-detectors or CCD sensors. After the intensity of reflected light has been recorded, the distribution of the recorded intensity is always statistically analysed. And as a result of the analysis, a roughness index, which depends on the statistical algorithm used, will be calculated. Finally, a calibration curve relating the roughness index to the real surface roughness (often obtained with a stylus tracing instrument) will be established.
through a series of experiments. Although quite a few light scattering methods have been investigated and developed [48, 55-60], the principles are always similar. The only difference among these studies is that the index chosen to describe surface roughness may be different from one application to another. This also makes the algorithms for analysis of intensity distribution different from each other.

In general, this technique has been proven successful for metal surfaces. However, this technique has not been applied to wood surface roughness. That is probably due to the different reflectivity of wood from that of metal.

### 2.5.3.2 Speckle pattern analysis

Speckle pattern is referred to the random pattern of bright and dark regions that is observed when a surface is illuminated with a highly or partially coherent light beam [54] (See Fig. 2-23). The reason for that is when a coherent beam is reflected from a rough surface, the reflected light waves from different points on the surface interfere, with constructive interference producing bright speckles and deconstructive interference producing dark speckles.

![Fig. 2-23 Speckle technique][1]

Due to speckle patterns relying upon rough surfaces, they could be used to evaluate surface roughness. However, speckle patterns are random and could only be described in statistical terms. Hence, in general, they could be only used to measure random roughness, and a Gaussian distribution of surface heights is always assumed [61, 62].

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[1]: [Image](image_url)
A number of research has been reported on assessing surface roughness by analysis of speckle pattern [62-67]. Several techniques, which are based on speckle pattern analysis, have been investigated, such as speckle-contrast technique and spectral speckle correlation technique. The measurement range of speckle-contrast technique is reported to be between 0.010 to 0.150 μm, while the measurement range of spectral speckle correlation technique is between 0.5 to 5 μm [67]. The range of former is clearly too small. But the latter is reported to be very sensitive to misalignment and vibrations [63].

The procedure for speckle pattern analysis is similar to that for the light scattering technique, which is: deriving an optical roughness indicator from the speckle pattern image, then correlating the indicator with real surface roughness obtained with other methods. If the correlation coefficient is high enough, then the roughness indicator is acceptable to describe surface roughness.

The speckle pattern analysis technique has been successfully used in evaluating metal surface roughness. But no applications have been found in evaluating wood surface roughness. However, Paul Wahl [68] applied speckle pattern analysis to investigate microcracks on wood surfaces. The idea of this research is that the intensity distribution of speckle pattern images will vary remarkably around microcracks.

2.5.3.3 Interferometry

Interferometry is based on interference phenomena where the amplitudes of two overlapping waves are systematically attenuated or reinforced according to their relative phase shift. The principle of interferometry is illustrated in Fig. 2-24. A signal beam is split into two beams. One beam is projected to the object and reflected back. The reflected beam then interferes with the other beam, which has travelled a known reference path. Given that the distance between the object and the beam splitter is \( Z \), then the intensity of the interference pattern \( I \) is defined by

\[
I = 1 + a \cos\left(\frac{2\pi Z}{\lambda}\right) \tag{50},
\]

Eq. 2-1

where \( \lambda \) is the wavelength of the signal beam and \( a \) is a constant. From Eq 2-1, distance \( Z \) can be obtained by
\[ Z = \frac{\lambda}{2\pi} \cos^{-1}\left( \frac{I-1}{a} \right) [50]. \]

Eq. 2-2

Fig. 2-24 Interferometry principle [50]

As seen in Eq. 2-2, the object range is measured with the signal wavelength \( \lambda \) as its yardstick. Therefore, interferometers can be very accurate when \( \lambda \) is very small. As seen in Eq. 2-1, however, since intensity \( I \) is a periodic (cosine) function of \( Z \), the measurement shown in Fig. 2-24 is only unique over a range of \( \lambda/2 \) (half of the wavelength of the signal beam) and is periodic with period \( \lambda \). Because of the periodicity, interferometry can only be used for obtaining absolute range measurements over finite ranges. Often it is used instead to obtain relative range measurements [50].

Due to their very limited measurement range, simple single-wavelength interferometers are only used in special applications such as lens testing where the submicrometer resolution is critical. However, the period \( \lambda \), which determines the measurement range, can effectively be extended by using a signal beam made of multiple wavelengths or by using a modulated signal beam. For the former, if two separate wavelengths \( \lambda_1 \) and \( \lambda_2 \) are employed, the combined measurement is still periodic but with a period of

\[ \lambda_p = \frac{\lambda_1 \lambda_2}{\lambda_2 - \lambda_1} [50]. \]

Eq. 2-3

If \( \lambda_2 - \lambda_1 \) is small, then \( \lambda_p \gg \lambda_1 \) or \( \lambda_2 \). For the modulated interferometry, the effective wavelength of the signal beam is changed by means of modulation. The output signal is still a periodic function, whose period is equal to the modulation wavelength, which is typically up to kilometres [50].
In general, interferometers can be an extremely accurate tool. However, measurement range of interferometers is limited by their effective wavelength. By using some techniques such as combination of multiple wavelengths or modulation, the measurement range can be greatly extended. There have been commercial interferometric systems, covering the distance scale from nanometers to kilometres [50].

2.5.4 Range imaging techniques

2.5.4.1 Introduction

Measuring waviness is a little different from evaluating roughness. Roughness is always described as an index such as Ra or Rq, which is a statistic value over an area. No one will be particularly interested in individual tiny details on the surface to be evaluated. Waviness can be described as frequencies and amplitudes, which are usually results of frequency-domain analysis such as in Maycock’s research. However, when every single wave on a surface is measured for evaluation of surface waviness, the measurement becomes a sort of measuring surface shapes, which falls within the category of range finding. Range imaging is currently the primary range finding technique, and has been widely studied.

A range imaging sensor is any combination of hardware and software capable of producing a range image of a real world scene under appropriate operating conditions. A range image is a large collection of distance measurements from a known reference coordinate system to surface points on object(s) in a scene. Range images are known by many other names depending on context: range map, depth map, depth image, range picture, rangepic, 3-D image, 2.5-D image, digital terrain map (DTM), topographic map, 2.5-D primal sketch, surface profiles, xyz point list, contour map, and surface height map [69]. According to Besl, six different optical principles have been used to actively obtain range images [69]:

- Imaging radar
- Triangulation
- Moiré
- Holographic interferometry
- Focusing
- Fresnel diffraction
According to [69], imaging radar is mainly for detecting shapes of objects with a low range resolution (typically in the order of mm) within a large detection range (up to 100 m). However, there is also an imaging radar metrology system reported in [69], which measures to an accuracy of 50 \( \mu \)m over a range of 2.5m. There has been some research on 3D sensing of rough surfaces by coherence radar [70], which is essentially a 3D sensor based on interferometry with a broadband light source.

Triangulation technique can be implemented in different manners, but it always requires structured illumination. When the structured illumination is a point of light, then the triangulation technique is laser displacement sensor discussed in Section 2.2.2. When the structured illumination is a line of light, then the technique becomes the light sectioning technique. Triangulation with a point of light or a line of light has a problem of low data rate and necessity of scanning the object under test. In order to overcome the problem, a grid of light points or multiple light stripes have been used as structured illumination.

Fringe projection and moiré are well developed techniques for measurement of surface profiles. These techniques will be discussed in Section 2.5.4.2.

Holographic interferometry features very high accuracy (down to 0.1 nm) and a small depth of field (typically 100 \( \mu \)m) [69]. Therefore, the measured object surface must be very flat and smooth.

Focusing mainly uses autofocus technique to determine range, which has been discussed in Section 2.2.1. Fresnel diffraction technique essentially employs Talbot effect to determine depths of 3-D objects. This technique will be discussed in Section 2.5.4.3.

2.5.4.2 Fringe projection and moiré techniques

When parallel fringes are projected onto the object surface, either by a conventional imaging system or by coherent light interference patterns, if the projection and viewing directions are different, the phase distribution of the measured fringe pattern will include information on surface heights of the object. The sensitivity of this technique can be improved by using line gratings: the technique is then referred to as projection moiré [71].

The key issue in fringe projection technique is how to extract information on surface heights from the fringe pattern. Usually, the fringe pattern is converted to a phase map by demodulation of the fringe image, and then an algorithm known as unwrapping is used to
retrieve the 3D surface [71, 72] In order to deal with discontinuities on the surface, phase-shifting projection is used in [71, 72] In some researches [73, 74], gray-code light projection is used in conjunction with phase-shifting.

Fringe projection technique also has some other variations. For example, in [75], fringe patterns are recorded at two viewing angles. This is similar to stereoscopy in a sense, which is essentially based on the triangulation principle. In addition, retroreflective projection gratings are used in [76, 77] to inspect quasi flat and specular surfaces. In [78], a TDI (Time Delay and Integration) system is used in conjunction with temporal modulation of a laser light source to produce fringe patterns on a moving object surface.

In general, the above research uses conventional projectors to produce fringes. In contrast, the following research uses line gratings, i.e. moiré techniques. A moiré pattern is a low spatial frequency interference pattern created when two gratings with regularly spaced patterns of higher spatial frequency are superimposed on one another [69]. There are two basic types of moiré techniques: projection moiré and shadow moiré. Projection moiré configuration is illustrated in Fig. 2-25. If $p_0$ is the period of the projected fringes at the object surface, then the change in $z$ between the centres of the interference fringes viewed by the camera is given by

$$\Delta z = \frac{p_0}{\tan(\theta_i) + \tan(\theta_s)} \quad [69].$$

Eq. 2-4

Projection moiré is usually implemented along with phase gratings, because a phase grating will often produce a higher contrast pattern with greater light efficiency than will an amplitude grating [79, 80].

The shadow moiré is the same as projection moiré except only a single large grating is needed. The surface is illuminated through the grating and viewed from another direction through the same grating [81, 82]. There are also some other moiré techniques such as Single Frame Moiré With Reference and Multi-frame Phase-shifted Moiré. More discussion on these moiré techniques is referred to [69]. There is one point about moiré techniques worth noting: moiré techniques are in general only useful for measuring smooth surfaces that does not exhibit depth discontinuities [69].
2.5.4.3 Fresnel Diffraction technique

Fresnel diffraction technique is based on Talbot effect, which is shown in Fig. 2-26. If a line grating, expressed as \( T(x,y) = T(x+p,y) \) with period \( p \), is illuminated with coherent light, exact in-focus images of the grating are formed at regular periodic intervals \( D = 2p^2/\lambda \) when \( p \gg \lambda \) [69]. The grating as shown in Fig. 2-26 is a cosine grating, which produces 180° phase shift Talbot images at \( D/2 \) intervals. The unambiguous ranging interval for such a range sensor is \( D/4 \); and in the interval, the distance between the object surface and the grating relates to the variation of local contrast in the image. Therefore, it is possible to measure distance between the object and the grating by measuring the variation of contrast in the image.

![Diagram of Fresnel Diffraction technique](image)

Fig. 2-26 Talbot effect or self-imaging property of gratings for range imaging [69]
Chavel and Strand [83] developed a technique, which was based on the above principle. As an example, a solenoid, which was 11 mm in diameter and 15 mm long, was measured. In the experiment, the positional error relative to the Talbot distance \( D \) was < 0.4%. The accuracy associated with this technique normally scales with the Talbot distance \( D \), but it is independent of a total absolute range [83], i.e., measurements in the tenth image region are as accurate as those in the first Talbot image region. Leger and Snyder also developed a similar technique to do depth measurement [84]. In Leger and Snyder’s experiment, a pairs of gratings crossed at right angles was used to provide two independent depth measurement channels. A real-time white light processor was developed to convert the two channels of depth information into pseudocolor, which was easily displayed. Leger and Snyder’s method was more qualitative than quantitative.

However, the measurement range for machined wood surfaces, which is actually the maximum variation of surface heights, is within about 20 \( \mu \)ms for not too coarse surfaces. Although it may not be difficult in theory to obtain a diffraction grating that is able to provide an appropriate unambiguous ranging interval along with a sharp enough contrast in the interval, nevertheless an inevitable problem in practice is that the vibrations associated with in-process measurement may very well move the sample surface in a range larger than the unambiguous ranging interval. This makes this method in doubt. However, it may be worth some experiments.

### 2.6 Summary

In this chapter, relevant methods and techniques for measuring wood surface roughness and waviness are reviewed. The conventional stylus tracing technique is not suitable for in-process measurement. The laser displacement sensor has been fully investigated. Although the Light Sectioning method was studied many years ago, the method is yet to further investigate, especially with the latest machine vision technologies. Therefore, the Light Sectioning method will be further studied in Chapter 5.

The Shadow Analysis method has been successfully investigated, especially by Hoffmeister et al. However, there are some different opinions about the algorithm used by Hoffmeister et al. In addition, only cutter mark widths are measured in Hoffmeister’s research. Clearly, it is worth to investigate whether cutter mark heights can be measured with the Shadow Analysis method. All these will be discussed in Chapter 6.
In Chapter 7, the Photometric Stereo method and the Shape From Shading method will be studied. These methods are not reviewed in this chapter because no literature is found on applying these methods to wood surface measurement. A review on the Photometric Stereo method and the Shape From Shading method will be given in Chapter 7.
3. Test rig development

This chapter describes the test rig developed to test the methods investigated in Chapter 5, Chapter 6 and Chapter 7. The description begins with an overview of the test rig, and then details the important components of the rig in respective sections. In the last section of the chapter, the way the wood samples are prepared is described, and the cutting machine is briefly introduced.

3.1 Overview

The test rig has two setup versions, one for the Shadow Analysis method and the Photometric Stereo method, as shown in Fig. 3-1, and the other for the Light Sectioning method, as shown in Fig. 3-2. As shown in the figures, the test rig consists of:

- Camera stand
- Camera and lens
- Sample and sample stand
- Light source and light source power supply
- Goniometer and light source stand

![Fig. 3-1 Test rig setup 1](image-url)
The only difference between test rig setup I and II is that different light sources are used. For setup I, the light source consists of a laser and a beam expander, while for setup II, the light source consists of a laser and a line generator. These light sources will be described respectively in the following sections.

### 3.2 Camera

The camera is a monochrome CMOS FireWire (IEEE1394) camera. The resolution of the camera is up to 1280x1024, and the sensor size is 2/3". Because the camera supports FireWire (IEEE1394), no frame grabber is needed. Instead, a FireWire adaptor card is required in the host PC.

In this research, red laser is used as light source. From this point of view, a color camera may benefit the image quality. However, color images are usually stored as 32-bit images, and therefore take up significantly more storage space than 8-bit or 16-bit monochrome images. Furthermore, color images will make image processing much more complex. Actually, only intensity of reflection from the sample surface is important for the methods investigated in this research. Color information is not critical, and grayscale
intensity information is adequate to extract all necessary information from an image. Therefore, a monochrome camera is selected.

This camera is a CMOS camera. CMOS cameras have CMOS microchips as imaging device. The CMOS technology is different from the traditional CCD in some aspects. Traditionally, CMOS imagers are designed for consumer products due to the low cost and low quality. However, with the rapid development of CMOS imaging technology, CMOS imagers have been accepted in industrial applications. In [85] there is a comparison of CCD and CMOS imagers. In summary, the comparison is as follows:

Table 3-1 Comparison of CMOS imagers and CCDs

<table>
<thead>
<tr>
<th></th>
<th>CMOS vs CCD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Responsivity</td>
<td>CMOS imagers are marginally superior</td>
</tr>
<tr>
<td>Dynamic range</td>
<td>CCDs are superior by a factor of two</td>
</tr>
<tr>
<td>Image quality</td>
<td>CCDs are significantly superior</td>
</tr>
<tr>
<td>Uniformity</td>
<td>CCDs are superior in general</td>
</tr>
<tr>
<td>Shuttering</td>
<td>CCDs are superior</td>
</tr>
<tr>
<td>Speed</td>
<td>CMOS imagers are superior</td>
</tr>
<tr>
<td>Windowing</td>
<td>CMOS imagers are superior</td>
</tr>
<tr>
<td>Anti-blooming</td>
<td>CMOS imagers are superior</td>
</tr>
<tr>
<td>Reliability</td>
<td>CMOS imagers are superior, although CCDs are also reliable</td>
</tr>
<tr>
<td>Cost</td>
<td>CMOS imagers are cheaper in general</td>
</tr>
</tbody>
</table>

In [85], CCDs are said to be superior to CMOS imagers in dynamic range. This is not always the case. For CMOS imagers with LINLOG™ technology, dynamic range can be up to 120 dB, which CCDs cannot reach. The camera used in the research has a dynamic range of >100 dB.

A camera with large dynamic range is particularly useful in this research. The background of the scene will be generally dark, while the reflection of laser light can be extremely bright in contrast. Therefore, large dynamic range means less blooming and high quality of images.

The sensor size of the camera is 2/3". In contrast, there are many cameras with a 1/2" or even 1/3" sensor size. The advantage of large sensor size is that when the resolution is the same, the pixel size of a larger sensor will be larger than that of a small sensor, which
means better sensitivity and relatively low quality lens is needed. This will be further discussed in Section 3.3

This camera has a global shutter in contrast to rolling shutters with early CMOS cameras. Global shuttering means the whole imaging sensor will be readout at the same time, while rolling shuttering means the sensor can only be readout in an integrating window rolling across the sensor. Cameras with a rolling shutter cannot image fast moving samples properly. Although only static samples have been tested in this research, moving samples are the ultimate targets. Therefore, a global shutter will be useful in the future research.

Another advantage of CMOS cameras is windowing. Information can be read out from a small window of the sensor. The benefit of it is high frame rates. Windowing is useful in the Light Sectioning method. As seen in the images shown in Chapter 5, the area of interest (AOI) is only a small portion of the whole image. With windowing, small images can be taken at a higher frame rate. This is useful in a real working condition with fast moving samples.

Images are taken with an image capturing software accompanying the camera. The software provides many camera control and image pre-processing functions. The taken images are all stored in BMP format. Although BMP format takes up more space than compressed format such as JPG, it has no information loss. The images are processed with MATLAB Image Processing Toolbox.

3.3 Lens

The lens employed is a 2/3" F/1.4 25 mm megapixel lens. In this section, the specifications of the lens are discussed in detail.

Megapixel lens means that the lens matches megapixel cameras. As mentioned before, the camera can take up to 1.3 million (1280x1024) pixel pictures. In order to make the 1.3 million pixels meaningful, the lens must feature an MTF (modulation transfer function) matching the pixel size.

A perfect lens would fully reproduce an image from an object with absolutely no degradation. However, a perfect lens does not exist. Sharpness, contrast, illumination, spectral transmission and distortion all affect the ability of a lens to reproduce an image. A lens can adequately reproduce an image from an object until it reaches a point where
the image detail can no longer be reproduced from the object. In other words, the lens can only resolve so much detail in terms of spatial frequency. The greater the amount of detail in the object, the higher the spatial frequency of the image. MTF (Modulation Transfer Function) is a measure for the amount of detail a lens can resolve. MTF is measured as a percent on a scale from 0% to 100%. 0% indicates a dark line and 100% indicates a white line. The optical industry standard for measuring MTF uses a spatial frequency unit called ‘line pairs per millimetre’ or lp/mm. With the details in objects getting finer, the resolving ability of a lens decreases. The contrast between the bright and the dark drops so that at some point it becomes impossible to discern the bright feature and the dark feature. More information about MTF can be found in [86].

The CMOS sensor has a 6.7 μm pixel pitch. The rule of thumb for the maximum line pair number that an imaging sensor can resolve is [87]:

$$R = \frac{1}{2 \times P} \text{ (lp/mm)}$$

Eq. 3-1

where $R$ = maximum line pair number, and $P$ = pixel pitch.

Therefore, the maximum line pair number that a lens must provide in order to match the camera is 75 lp/mm. The lens employed features 200 lp/mm at the centre and 160 lp/mm at the corners. Therefore, the lens is able to meet up the resolving requirement of the image sensor.

That the lens is a 2/3" lens means the lens can illuminate an area of 2/3 inch in diagonal. This matches the size of the CMOS sensor.

F-number is defined as the ratio of focal length to clear aperture. The larger the number, the more light can be allowed to get into the camera. With the F-number F/1.4, the lens allows the camera to work at a very low level of illumination. This is also very helpful when the sample is moving and the exposure time has to be very short.

Another important specification of a lens is distortion. The lens employed is designed to offer very low distortion. This will be further discussed in Section 3.6.

### 3.4 Goniometer and light source stand

For all the methods investigated in this research, an ability to adjust the angle of incidence of light is desirable. For this purpose, a goniometer is designed. The assembly
drawing of the goniometer is attached in Appendix F. Simply speaking, there is a micrometer in the goniometer that makes the precise adjustment possible. Calibration of the goniometer is carried out with the goniometer fixed on the light source stand. The calibration is conducted with a CMM (Coordinate Measuring Machine). The calibration result is shown in Table 3-2. The first column of the table is the micrometer readings with 0.5 mm as steps. The second column is the angles between the goniometer and the reference plane, which in here is the base plane of the light source stand. The third column is the magnifications calculated with the angles in the second column. The calculation is referred to the triangulation relationship shown in Fig 2-14.

Table 3-2 Calibration of the goniometer

<table>
<thead>
<tr>
<th>Micrometer reading (mm)</th>
<th>Angle (°)</th>
<th>Magnification</th>
</tr>
</thead>
<tbody>
<tr>
<td>10 465</td>
<td>0</td>
<td>Inf</td>
</tr>
<tr>
<td>9 465</td>
<td>0.5730</td>
<td>99 9950</td>
</tr>
<tr>
<td>8 465</td>
<td>1.1460</td>
<td>49 9900</td>
</tr>
<tr>
<td>7 465</td>
<td>1.7191</td>
<td>33 3183</td>
</tr>
<tr>
<td>6 465</td>
<td>2.2924</td>
<td>24 9800</td>
</tr>
<tr>
<td>5 465</td>
<td>2.8660</td>
<td>19 9750</td>
</tr>
<tr>
<td>4 465</td>
<td>3.4398</td>
<td>16 6366</td>
</tr>
<tr>
<td>3 465</td>
<td>4.0140</td>
<td>14 2507</td>
</tr>
<tr>
<td>2 465</td>
<td>4.5886</td>
<td>12 4599</td>
</tr>
<tr>
<td>1 465</td>
<td>5.1636</td>
<td>11 0660</td>
</tr>
<tr>
<td>0 465</td>
<td>5.7392</td>
<td>9 9499</td>
</tr>
</tbody>
</table>

3.5 Light source

Two types of light sources are used in the research. For the Light Sectioning method, a laser line generator is employed. For the Shadow Analysis method and the Photometric Stereo method, a spot laser is employed along with a beam expander.

3.5.1 Laser line generator

This laser line generator consists of a diode laser and a line generator head. The laser is a red laser with a wavelength of 670 nm. The line generator head features a patented Powell glass lens designed to generate lines without a Gaussian profile. In contrast, a line produced by an ordinary laser line generator exhibits a Gaussian intensity profile along
the length of the line. A comparison of intensity profiles produced by a Gaussian line generator and a non-Gaussian line generator is shown in Fig. 3-3. For the Light Sectioning method, an even intensity line will clearly benefit the method, as the edge finding algorithm in the Light Sectioning method relies on the intensity variation from illuminated areas to dark areas. As discussed in Chapter 5, a Gaussian line as shown in Fig. 3-3 (A) will introduce errors and make the edge finding task much more complex.

Although the line generated by the laser is without a Gaussian profile, it is only the case along the length of the laser line. Across the widths of the laser line, there are still Gaussian profiles. However, this does not affect the edge finding algorithm, for the profile can be extracted through linking all the peaks on the Gaussian profiles one by one along the length of the laser line.

![Intensity Profiles](image)

Fig. 3-3 (A) Gaussian line (B) non-Gaussian line

### 3.5.2 Spot laser and beam expander

The spot laser is an ordinary diode laser with a wavelength of 670 nm. The light generated by the laser is collimated with a spot size of 4.5x2.5 mm. This laser is used for the Shadow Analysis method and the Photometric Stereo method. These two methods require an area of at least 20x16 mm on the sample surface to be illuminated. Clearly, the
spot laser cannot provide an adequate illumination area on its own. Therefore, a beam expander is necessary.

There are some beam expanders on the market. But those beam expanders are generally too large to be fixed on the goniometer. Therefore, a specific beam expander is designed. The design is conducted with an optical CAD program known as WinLens from LINOS Photonic.

The requirements for the beam expander are:

- Adequate magnification
- Compact design
- Easy to accommodate the spot laser
- Easy to be fixed on the goniometer

The first parameter for the beam expander to design is the magnification. The cross section of the laser beam is an ellipse with 4.5 mm and 2.5 mm as its major axis and minor axis respectively. The expanded beam is expected to be about 30 mm in its major axis. Therefore, the magnification must be greater than 6x. The actual magnification depends on the selection of lenses, which in turn is affected by the dimensional limit that the goniometer imposes on the beam expander. Therefore, the final magnification can only be determined after selection of lenses.

There are two types of beam expanders [86], as shown in Fig 3-4. With both type A and B, the magnification is

\[ M = \frac{f_2}{f_1} \]  

but for type A the overall length of the optical system is

\[ L = f_1 + f_2 \]  

Eq. 3-2

Eq. 3-3

while for type B, the overall length of the system is only

\[ L = f_2 - f_1 \]

Eq. 3-4
Clearly, type B beam expander shown in Fig. 3-4 has shorter overall lengths of the optical system than type A beam expander provided the magnification is the same. Therefore, a type B beam expander is chosen as it can meet the requirement of compact design.

Several lens pairs are selected as candidates and the optical performance of the candidate lens pairs is simulated in WinLens. The following aspects of performance of the candidate lens pairs are compared:

- The overall length of the optical system
- The diameter of the positive lens
- Aberration

Finally, the beam expander is designed as illustrated in Fig. 3-5. The specifications for the lenses are listed in Table 3-3. Note that the positive lens is a doublet lens comprised of a negative lens and a positive lens. The benefit of doublet lenses is less aberration compared to singlet lenses.
According to Eq 3-2, the magnification of the beam expander is $\frac{60}{9} = 6.67$. The expanded beam diameter is $4.5 \times 6.67 = 30$ mm. This meets the requirement of magnification. In addition, the spacing measured from the second surface of the negative lens to the first surface of the positive lens is only about 41 mm. This meets up the requirement of compact design.

After the optical design of the beam expander comes the mechanical design for the housing of the beam expander, which is illustrated in Fig. 3-6. The real spacing between the negative lens and the positive lens affects the collimation of the output light. It is impossible to make the real spacing identical to the ideally calculated value. Therefore, a mechanism of adjustment for the spacing of lenses is necessary. As shown in Fig. 3-6, the positive lens assembly has a thread connection with the barrel, therefore it can be threaded in or out, and it can be locked with the locker. This mechanism proves very useful in adjustment of collimation of light produced by the beam expander.
Although a laser beam can be collimated at the output of the optics, the beam will diverge when it propagates. This is due to diffraction of light, which causes light waves to spread transversely as they propagate. The spreading of a laser beam is in precise accord with the predictions of pure diffraction theory, which is expressed as \[ w_z = w_0 \left[ 1 + \left( \frac{\lambda z}{\pi w_0^2} \right)^2 \right]^{\frac{1}{2}} \]  

Eq. 3-5

where:

- \( \lambda \) is the wavelength of the laser beam;
- \( w_0 \) is the beam waist, i.e. the minimum radius of the laser beam;
- \( z \) is the distance from the beam waist;
- \( w_z \) is the radius of the beam measured at the distance \( z \) from the beam waist.

This characteristic is illustrated in Fig. 3-7. Note that \( w_0 \) and \( w_z \) are radii. The angle \( \theta \) is the asymptotic angle of the beam divergence.
The purpose of introducing laser beam propagation is to calculate how much the laser beam coming out of the beam expander will eventually diverge. In the experiment, the distance from the beam expander to the surface covered by the camera FOV is about 200 mm. The wavelength of the laser is 670 nm. The output beam diameter is 30 mm, so the beam waist \(w_0\) is \(30/2 = 15\) mm. According to Eq. 3-5, the beam radius measured at 200 mm away the beam expander is

\[
\begin{align*}
  w_z &= 15 \times \left[ 1 + \left( \frac{6.7 \times 10^{-4} \times 200}{\pi \times 15^2} \right)^2 \right]^{1/2} \\
  &\approx 15.000
\end{align*}
\]

Eq. 3-6

The beam radius \(w_z\) measured at 200 mm from the beam expander is almost the same as the beam waist \(w_0\). It can be concluded that the laser beam divergence resulting from the diffraction is so small that it can be safely ignored.

### 3.5.3 Calibration of the beam expander

As mentioned in the last section, to what extent the laser beam is collimated depends on the real distance between the two lenses. There is an adjusting mechanism for collimating the laser beam. This section discusses how to precisely collimate the laser beam.

Since a laser beam measurement instrument is not available, a small ng is constructed as shown in Fig 3-8 to measure and adjust the collimation. The camera discussed above, the beam expander and a translucent screen are located on a slide guide. The screen is also shown in the insert. The distance between the camera and the screen is fixed, and the beam expander can move along the guide.
The principle is that the beam expander projects expanded laser beam onto the translucent screen from one side, and the camera takes images of the beam projection from the other side. If the beam is collimated, then the beam imaged on the camera will not change in size while the beam expander moves away from the screen or towards to screen along the guide. Otherwise, the beam is not collimated.

The beam size is measured by means of intensity sum of the beam image. Not precisely but largely, intensity sum of the beam image is proportional to the beam size.

In fact, however, it is almost impossible to make the beam absolutely collimated. In addition, even if the beam is collimated, noise in the camera will still make the beam images slightly different from one another, and therefore giving slightly fluctuant intensity sums. Therefore, the strategy used is not to make perfect collimation, but as good as possible.

The distance between the camera and the screen is about 140 mm. Every time after the beam expander is re-adjusted, five images are acquired with the distances between the screen and the beam expander being 40 mm, 140 mm, 240 mm, 340 mm, and 440 mm.
respectively. Then, the beam sizes are calculated from the five images. If the beam sizes vary in a large range, then adjust the positive lens assembly relative to the barrel accordingly. The procedure for collimating the beam expander is as follows:

1. Adjust the positive lens assembly arbitrarily.
2. Take images with distance between the beam expander and the screen being 40 mm, 140 mm, 240 mm, 340 mm, and 440 mm respectively.
3. Count the beam sizes from the five images.
4. Does the beam diverge or converge?
   - If divergence, thread out the positive lens assembly.
   - If convergence, thread in the positive lens assembly.
   - If neither diverges nor converges, the procedure is complete.

Fig. 3-9 Procedure for collimating the beam expander

In the last step, the condition 'neither diverges nor converges' means the beam does not have a clear trend that it is divergent or convergent. At this point, the variation of beam size is mainly due to image noise. In reality, it may need many loops before the best collimation is achieved. In order to be more efficient, when the variation of beam sizes among the five images is smaller than a threshold, the beam can be considered collimated.

Fig. 3-10 shows four beam size variations against the distance between the beam expander and the screen. Line 1 clearly represents a divergent beam. Line 2 clearly shows convergence. Line 3 and line 4 indicate a slight divergence, but they also show some
convergence at the near distances. Line 4 is considered the best, for within the first 200 mm the variation of beam size is less than 1% of the intensity sum.

![Graph showing the variation of intensity sum with distance](image)

**Fig. 3-10 Collimation of the laser beam**

3.6 Camera calibration

Camera calibration is a big topic in computer vision community. There are many literature references in this field, such as [88-91]. Here, camera calibration actually encompasses calibration of the whole imaging system including the camera and the lens. Strict camera calibration is very complicated, and there is no standard for camera calibration. In this section, a brief introduction to camera calibration will be presented first, and then a simplified camera calibration procedure employed in this research will be described.

3.6.1 Theory

In summary, camera calibration is all about getting the best geometric information from your images. When an imaging system is designed, it is easy to assume every part in the system is perfect. For instance, focal length is assumed the figure given by the manufacturer; the optical axis is aligned with the imaging sensor; the camera is normal to the surface to be imaged. In reality, however, almost everything in the system is more or less different from the perfect condition. The result is that the image looks different from
what it is expected. A simple example is that a straight line in real world becomes bent in the image (Fig. 3-8 is a good example) This may not be a problem for some imaging tasks, but it is a problem for some others such as geometric measurements.

Generally, there are two sets of parameters to calibrate: intrinsic parameters and extrinsic parameters.

### 3.6.1.1 Extrinsic parameters

The extrinsic parameters involve transforming points in the real world coordinate system, also termed as object coordinate system, into camera coordinate system. This transform is illustrated in Fig. 3-11. The origin of the camera coordinate system is at the projection centre. The Z-axis of the camera coordinate system is perpendicular to the image plane.

![Fig. 3-11 Object coordinate system and camera coordinate system](image)

Let $P_o$ be a point at location $(x_o, y_o, z_o)$ in the object coordinate system, and at location $(x_c, y_c, z_c)$ in the camera coordinate system. The transform from the object coordinate system to the image coordinate system consists of two operations: rotation and translation. Suppose the origin of the object coordinate system is at $(x_o, y_o, z_o)$ in the camera coordinate system, and the object coordinate system rotates $\omega$ around $X$-axis, $\phi$.
around Y-axis, and \( \kappa \) around Z-axis to be in alignment with the camera coordinate system, then the transform is expressed as follows [88]:

\[
\begin{bmatrix}
    x_c \\
    y_c \\
    z_c
\end{bmatrix} =
\begin{bmatrix}
    m_{11} & m_{12} & m_{13} \\
    m_{21} & m_{22} & m_{23} \\
    m_{31} & m_{32} & m_{33}
\end{bmatrix}
\begin{bmatrix}
    x_o \\
    y_o \\
    z_o
\end{bmatrix} +
\begin{bmatrix}
    x_0 \\
    y_0 \\
    z_0
\end{bmatrix}
\]

Eq. 3-7

where

\[
\begin{align*}
    m_{11} &= \cos \varphi \cos \kappa \\
    m_{12} &= \sin \omega \sin \varphi \cos \kappa - \cos \omega \sin \kappa \\
    m_{13} &= \cos \omega \sin \varphi \cos \kappa + \sin \omega \sin \kappa \\
    m_{21} &= \cos \varphi \sin \kappa \\
    m_{22} &= \sin \omega \sin \varphi \sin \kappa - \cos \omega \cos \kappa \\
    m_{23} &= \cos \omega \sin \varphi \sin \kappa - \sin \omega \cos \kappa \\
    m_{31} &= -\sin \varphi \\
    m_{32} &= \sin \omega \cos \varphi \\
    m_{33} &= \cos \omega \cos \varphi
\end{align*}
\]

The purpose of camera calibration is to determine translation vector \((x_0, y_0, z_0)\), and rotation angles \(\omega, \varphi\) and \(\kappa\).

3.6.1.2 Intrinsic parameters

The intrinsic parameters include:

- Focal length: the real focal length may be slightly different from the one given by the manufacturer
- Principal point: the point where the optical axis intersects the image plane. This point is rarely at the centre of the image
- Aspect ratio: this aspect ratio is not the aspect ratio of the image, but the aspect ratio of the pixel. If the pixel is square, then the aspect ratio is 1
- Skew coefficient: the skew coefficient defines the angle between the x and y axes of the pixel
- Distortions: distortions include radial distortion and tangential distortion. Radial distortion can be classified as barrel distortion, pincushion distortion, and a combination of barrel and pincushion distortion.

Among above parameters, distortion is a major concern. Among distortions, radial distortion is a major type. Tangential distortion, due to decentering of lens elements, is typically about 15% of the size of radial distortion [91].

Radial distortion is modelled by an even series polynomial [92].

\[
\begin{pmatrix}
R_x \\
R_y
\end{pmatrix}
= (k_1r_0^2 + k_2r_0^4 + k_3r_0^6 + \ldots) \begin{pmatrix}
x_0 \\
y_0
\end{pmatrix}
\]

where \((x_0, y_0)\) are coordinates of a point before considering radial distortion; \(R_x\) and \(R_y\) are radial distortion at the point in X-axis and Y-axis respectively; \(k_1, k_2, \text{and } k_3\) are coefficients for 2\(^{nd}\) order, 4\(^{th}\) order and 6\(^{th}\) order radial distortion; \(r_0 = \sqrt{x_0^2 + y_0^2}\).

Tangential distortion is modelled as follows [92], with \(r_0, x_0, y_0\) having the same definitions as in Eq. 3-8, and \(T_x\) and \(T_y\) being tangential distortion in X-axis and Y-axis respectively.

\[
T_x = p_1[r_0^2 + 2x_0^2] + 2p_2x_0y_0
\]

Eq. 3-9

\[
T_y = p_2[r_0^2 + 2y_0^2] + 2p_1x_0y_0
\]

Eq. 3-10

Fig. 3-12 Coordinate systems in camera calibration
Fig. 3-12 illustrates an image plane and relevant coordinate systems. There are three coordinate systems involved: the camera coordinate system, the image coordinate system, and the pixel coordinate system. The image coordinate system is the camera coordinate system without Z-axis. The difference between the image coordinate system and the pixel coordinate system is that the origin of the image coordinate system is at the centre of the image plane, while the origin of the pixel coordinate system is at the upper-left corner of the image plane. There is a simple translation between the image coordinate system and the pixel coordinate system. There is another point worth noting: the principal point. The principal point is not always coincident with the origin of the image coordinate system; and one of the objectives in camera calibration is to find out the real position of the principal point.

Let \( P_0 \) be a point in the object space, and \( P_i \) be the imaged point of \( P_0 \) on the image plane, as shown in Fig. 3-12. \( P_0 \) is located at \((x_c, y_c, z_c)\) in the camera coordinate system, and \( P_i \) is at \((x, y)\) in the image coordinate system.

For the transformation from \( P_0 \) to \( P_i \), a model known as pinhole model is usually used to define the transformation in ideal conditions. The pinhole model is based on the principle of collinearity, where each point in the object space is projected by a straight line through the projection centre into the image plane [88]. According to the model, the transformation from \( P_0 \) and \( P_i \) is defined as:

\[
\begin{pmatrix}
\bar{x}_i \\
\bar{y}_i
\end{pmatrix} = \begin{pmatrix} x_c \\ y_c \end{pmatrix} \cdot \frac{f}{z_c} \quad [88]
\]

Eq. 3-11

where \( f \) is the focal length, and \((\bar{x}_i, \bar{y}_i)\) are the imaged point \( P_i \) at the ideal position.

When taking imperfect camera intrinsic parameters into consideration, the transformation becomes complicated. Although there have been quite a few camera models for defining the transformation, there has not been a unanimously accepted model, which encompasses all the camera intrinsic parameters. By combination of the models in [91, 93, 94, 95], the transformation from \( P_0 \) to \( P_i \) is then defined as:

\[
\begin{pmatrix}
x_i \\
y_i \\
1
\end{pmatrix} = \begin{pmatrix} \tau \cdot f & s \cdot f & x_{pp} \\
0 & f & y_{pp} \\
0 & 0 & 1
\end{pmatrix} \begin{pmatrix}
x_d \\
y_d \\
1
\end{pmatrix}
\]

Eq. 3-12
where \( r \) is aspect ratio, \( f \) is focal length, \( s \) is skew coefficient, \( x_{pp} \) and \( y_{pp} \) are the coordinates of the principal point, and \( x_d \) and \( y_d \) are defined as:

\[
x_d = \bar{x} + R_x + T_x
\]

\[
y_d = \bar{y} + R_y + T_y
\]

Eq. 3-13

Eq. 3-14

where \( R_x \) and \( R_y \) are derived with Eq 3-8, \( T_x \) and \( T_y \) are derived with Eq 3-9 and Eq. 3-10. Note that, in the above derivations, \( x_o \) and \( y_o \) in Eq. 3-8, Eq. 3-9, and Eq. 3-10 should be substituted with \( \bar{x} \) and \( \bar{y} \), computed with Eq. 3-11 respectively.

The purpose of camera calibration for intrinsic parameters is to derive focal lengths \( f \), aspect ratio \( r \), skew coefficient \( s \), principal point \( x_{pp} \) and \( y_{pp} \), and \( k_1, k_2, k_3 \ldots \) in Eq. 3-8, and \( p_1, p_2 \) in Eq 3-9 and Eq 3-10. There have been some methods for the derivation, which always involve very complicated mathematical operations. Descriptions on these methods for derivation of camera intrinsic parameters are referred to [91, 93, 94, 95].

### 3.6.2 Calibration of the imaging system used in the research

As mentioned at the beginning of Section 3.6, camera calibration is very complicated. This can also be seen in Section 3.6.1 and relevant references [91, 93, 94, 95]. However, the theories introduced in Section 3.6.1 are very generic, and some of the intrinsic parameters may not be necessary for most of image tasks. For example, it is now very common to assume square pixels, i.e. aspect ratio being 1 and no skew, due to modern imaging sensor manufacturing technology [91]; for radial distortion in Eq. 3-8, only 4\(^{th}\) order or even only 2\(^{nd}\) order is estimated, it is also reasonable to assume no tangential distortion [91], the principal point is assumed to be at the centre of the image plane. Following the common practice, in this research, only lens radial distortion is calibrated, with other intrinsic parameters being ignored. For the radial distortion, only 2\(^{nd}\) order is estimated, i.e. only \( k_1 \) is estimated.

There are two scenarios in which lens distortion can potentially affect the final result in this research. The first one is associated with the Light Sectioning method, while the second one with the Photometric Stereo method and the Shadow Analysis method.

For the Light Sectioning method, since the laser line is straight in the real world, the imaged line is supposed to be straight. But if the lens has a radial distortion, barrel or
pincushion, the imaged line will be bent upwards or downwards. This may affect the final light section extracted from the image.

For the Photometric Stereo method and the Shadow Analysis method, an ‘adding column by column’ algorithm is necessary. A requirement of the algorithm is that vertical lines need to be straight in the image, otherwise the sums of the columns will not reflect the real situation. As an example, a pincushion distortion is illustrated in Fig. 3-13. The dashed lines represent the real cutter marks, while the solid lines the imaged cutter marks. Clearly, the ‘adding column by column’ algorithm will not give a correct result if the distortion is too much.

![Fig. 3-13 Pincushion distortion](image)

Compared to the effects of lens radial distortion on the Photometric Stereo method and the Shadow Analysis method, the effects on the Light Sectioning method may be ignored, as the radial distortion in the centre of the lens is much smaller than on the corners of the lens. Since the light sections only take a narrow portion of the FOV, they can be imaged in the centre of the FOV.

Before calibration, there is another issue to consider. That is aligning camera normal to the calibration pattern plane. This involves calibration of extrinsic parameters.

Actually, calibration of the extrinsic parameters is only necessary for some vision tasks like robot guidance, which needs to transform coordinates in camera coordinate system into the real world coordinate system or the other way around. For the vision task involved in this research, it is not necessary to know the exact rotation and translation parameters. Only the angles $\omega$ and $\phi$ need to be known, or the camera can be fixed normal to the target plane.
In this research, no efforts are made to calibrate the angles $\omega$ and $\varphi$, but efforts are made to align the camera normal to the target plane. The principle of alignment is illustrated in Fig. 3-14.

![Diagram](image)

(A) Camera normal to the target plane  
(B) Camera skew to the target plane

**Fig. 3-14** Camera normal to the target plane and camera not normal to the target plane

Picture (A) in Fig. 3-14 shows a situation where the camera is perfectly aligned normal to the target plane. $O$ is the point where the optical axis of the camera intersects the target plane. Clearly, moving camera up and down will not affect the position of $O$. Picture (B) shows a camera skew to the target plane. When the camera is at height $H_1$, the optical axis intersects the target plane at $O_1$, and when the camera is at height $H_2$, the optical axis intersects the target plane at $O_2$.

As mentioned before, the optical axis is assumed coincident with the image centre. In order to mark the image centre, a crosshairs is superimposed on the image. A printed target with another crosshairs is put under the camera. An example of the crosshairs in the image and the crosshairs on the printed target is shown in Fig. 3-15.
Fig. 3-15 Crosshairs superimposed in the image and printed target with crosshairs

The procedure for the alignment is illustrated in Fig. 3-16 and in Fig. 3-17.

Fig. 3-16 Alignment of camera normal to the target plane
Fig. 3-17 Procedure for alignment of the camera normal to the surface

It should be noted that this alignment of camera normal to the target plane is not very strict in that overlap of the crosshairs is only judged by the eye. However, there is no particular reason the camera needs to be highly precisely normal to the target plane.

After the camera is aligned normal to the target plane, lens radial distortion is to be calibrated. Again, an approximate calibration is conducted. A calibration pattern is a rectangle printed on paper. As shown in Fig. 3-18, the rectangle shows a slight barrel distortion. (So does the image in Fig. 3-15.) After extracting the borders of the rectangle, it is found that the barrel distortion is about 2.5 pixels over the top border of the rectangle, which is shown in Fig. 3-19.
Fig. 3-18 Calibration of radial distortion

Fig. 3-19 Top border of the rectangle in Fig. 3-18
When only considering the 2nd order radial distortion, Eq. 3-15 and Eq. 3-16 can be derived from Eq. 3-8.

\[ x = x_0 + x_0 k_1 (x_0^2 + y_0^2) \]

Eq. 3-15

\[ y = y_0 + y_0 k_1 (x_0^2 + y_0^2) \]

Eq. 3-16

where \( x_0, y_0 \) are coordinates of a point in the ideal image, i.e. distortion-free image; \( x, y \) are coordinates of the corresponding point in the distorted image, \( k_1 \) is the coefficient for the 2nd order distortion.

Combination of Eq 3-15 and Eq. 3-16 gives

\[ r = r_0 + k_1 r_0^3 \]

Eq. 3-17

where \( r = \sqrt{x^2 + y^2} \), \( r_0 = \sqrt{x_0^2 + y_0^2} \). This equation indicates that radial distortion occurs radially.

By observation of Fig. 3-19, the barrel distortion of the lens is estimated to be about 2.5 pixels over 1207 pixels for the top border in Fig. 3-18. In order to undistort the image, it is necessary to determine the coefficient \( k_1 \) in Eq 3-15 and Eq. 3-16. Derivation of coefficient \( k_1 \) from Fig. 3-19 is illustrated in Fig. 3-20, where the curve is an approximation to the curve in Fig. 3-19. Note that X-axis and Y-axis in Fig. 3-20 are coordinates in pixels calculated from the centre of the image in Fig. 3-18. The point M is the highest point on the curve at approximately (0, 491.5). The leftmost point on the curve L is at (-603, 489) and the rightmost point R is at (603, 489).
The function for the curve in Fig. 3-20 is still unknown. However, it is known that the span of the curve, which is from -603 to 603 in X-axis, and the height of the curve, which is 25 pixels. It is also certain that the corrected line must be a straight line with no changes in Y-axis and the distortion occurs radially. Therefore, after undistortion, point M on the curve will move straight upwards to M₀, and L and R move radially to L₀ and R₀ respectively, as shown in Fig. 3-20.

Let the curve in Fig. 3-20 be \( f(x,y) \) and the straight line be \( g(x_0,y_0) \). It is already known that point M is at \((0, 491.5)\), point L is at \((-603, 489)\) and point R is at \((603, 489)\)

The procedure for deriving \( k_1 \) is illustrated in Fig 3-21. The algorithm is essentially an iteration process, in which the straight line in Fig 3-20 is firstly assumed to be known with an estimated \( M_0M \) distance \( b \), and \( k_1 \) can be derived from the point pair M and \( M_0 \), then distortion of the straight line can be derived with \( k_1 \); if the height of the distorted line is close to 25 within the tolerance \( \epsilon \), then the value of \( k_1 \) is the solution; if not, then the above procedure has to run again with the new estimated \( M_0M \) distance being \( b + \delta \). The step \( \delta \) is set to be 0.01 and the tolerance \( \epsilon \) is also 0.01. The iteration operation was implemented in MATLAB, so the operation symbols and functions in Fig. 3-21 are referred to MATLAB.
After \( k_1 \) become known, the distorted image in Fig. 3-18 can be corrected. Actually, undistortion can be seen as another distortion operation with an opposite effect, i.e., barrel distortion can be corrected with a pincushion distortion operation. This operation is expressed as:

\[
r_0 = r + kr^3
\]

Eq. 3-18

where \( r_0 \) is undistorted radius, \( r \) is distorted radius, and \( k \) is coefficient for the pincushion operation.

From Eq. 3-18, Eq. 3-19 can be derived.

\[
r_0 - r = kr^3
\]

Eq. 3-19

From Eq. 3-17, Eq. 3-20 can be derived

\[
r - r_0 = k_1r_0^3
\]

Eq. 3-20

Eq. 3-19 and Eq. 3-20 gives
\[ k = -k_1 \frac{r^3}{r^3} \] 

Eq. 3-21

Therefore, \( k \) can be derived from \( k_1 \). Note that \( k \) is different from \( k_1 \) in that \( k_1 \) is a coefficient, while \( k \) is a coefficient vector.

The consequent undistortion is conducted with Eq. 3-22 and Eq. 3-23.

\[ x_u = x + xk(x^2 + y^2) \] 

Eq. 3-22

\[ y_u = y + yk(x^2 + y^2) \] 

Eq. 3-23

After undistortion, the corrected image is shown in Fig. 3-22. In addition, the top border in the corrected image in Fig. 3-22 is extracted and plotted along the original top border in Fig. 3-23. Clearly, the barrel distortion has been largely corrected. The undistortion process has the similar effects on other borders in Fig. 3-18.

Fig. 3-22 Corrected image
3.7 Making wood samples

Wood samples are made with nominal cutter mark patterns for this research. Three species of wood are selected: beech, oak, and ramin. For each species, five samples are made with cutter mark widths of 1 mm, 1.5 mm, 2 mm, 2.5 mm, and 3 mm respectively. 

Wood samples are cut with a small planer. Detailed information on this planer can be found in [96]. Here only a brief introduction is given.

The planer consists of a spindle unit, an X-Y table (feed table), a control cabinet, and a PC. The spindle unit and the X-Y table are shown in Fig. 3-24. The spindle unit has a close-loop control, which is composed of two eddy current sensors and four piezo-actuators. (See Fig 3-25) Although there are four piezo-actuators mounted on the spindle unit, only the vertical mounted ones, i.e. actuator 1 and 3, are used due to some technical limitations. The close-loop control is meant to control the spindle vertical position in X-Z plane during the cutting process. For some of the samples used in the research, no spindle vertical vibration was intentionally stimulated; for the rest of the samples, spindle vertical vibration was stimulated so that surface waviness defects can be controllably implemented on the sample.
Fig. 3-24 Schematic of the planer [96]

Fig. 3-25 Piezo-actuators and eddy current sensors [96]
X-axis motion (feed) of the X-Y table is driven by a servomotor, and Y-axis motion is implemented by a hand wheel. The feed speed is set up via the PC. The spindle rotary speed is set up manually via an inverter. Clearly, both the feed speed and the spindle speed may drop below the setup values during the cutting process. Due to the limitation of the control units, however, only the actual spindle speed can be monitored during the cutting. In Appendix K, machining parameters for the samples used in Chapter 8 are presented. The spindle speeds are the actual values measured during the cutting, while the feed speeds are the set-up values. Therefore, the calculated cutter mark widths and heights in Appendix K may slightly be smaller than those given in the table.

Due to the limitation of the planer, the width of all the sample surfaces is about 12 mm, and the length of samples is about 200 mm.

At last, a problem with clamping samples on the X-Y table has to be discussed. The clamping layout is illustrated in Fig. 3-26. As shown in the figure, cutting takes place on one side of the sample, while the clamping force is exerted on the other side. If the sample top and bottom surfaces are flat and parallel to each other perfectly, there will be no problem. However, if these two surfaces are not in parallel, and especially when there is a warp on the bottom surface of the sample, then after clamped, there may be a clearance between the sample bottom surface and the X-Y table top surface on the cut side of the sample. When the sample is being cut, the cutter may push the sample downwards periodically, causing vibration defect on the surface. This will be discussed again in Chapter 8, when measured surface profiles show defect of this kind.

---

**Fig. 3-26 Clamping layout of the planer**
4. Exploration of a laser profilometer

In order to assess the performance of the methods discussed in the following chapters, a laser profilometer is used as a reference. In this chapter, the following contents are discussed:

- Principles of the laser profilometer
- Average of multiple profiles
- Surface analysis
- Problems with operating the laser profilometer

4.1 The laser profilometer

The instrument consists of three main components: a laser sensor and its interface, a X-Y table and its interface, and a computer (Fig. 4-1). Here, the focus is on the principles of the laser sensor.

The principles of the laser sensor are illustrated in Fig. 4-2. An infrared laser beam (780 nm) is focused on the measured surface, creating a laser spot of 2 μm in diameter. The reflection of the laser spot from the surface is collected by a set of lenses built in the sensor. As seen in Fig. 4-2, the projected laser beam and the reflected laser beam share
the same optics. However, there is a beam splitter in the sensor that directs the reflected beam into a focus detector. The focus detector generates a signal according to the focus level. Before a measurement, the distance between the laser sensor and the surface needs adjusting so that the laser spot is in sharp focus on the surface, which can be indicated with a series of LED indicators on the panel of the interface box that connects the sensor to a computer. During a measurement, the sample moves underneath the sensor. Due to the surface high variation, the distance between the surface and the sensor changes, which will cause the laser spot out of focus. Meanwhile, the focus detector generates a signal following the level of focus of the laser spot. The focus signal is linked to an auto-focus mechanism, which moves the objective in the sensor, as shown in Fig 4-2, until the laser beam is exactly focused on the surface again. The displacement of the objective is recorded with a displacement sensor. Clearly, the record of the displacement sensor represents a profile of the surface along where the sensor has scanned across.

![Fig. 4-2 The schematic of the laser sensor [8]](image)

The sensor has three measurement ranges and resolutions. In this research, the measurement range of ±30 µm and the resolution of 20 nm are used. More technical data of the sensor can be found in Appendix G.
The sensor interface, housed in an enclosure, functions as an intermediate layer between the laser sensor and the computer. The sensor interface provides signal filtering and amplification. The output of the sensor interface feeds into an ADC card in the computer, where the surface high data is digitised.

Similar to ordinary stylus instruments, this laser profilometer also needs scanning of the surface to be measured. The scanning mechanism is functioned by an X-Y table driven by step servomotors. The step motors are controlled by the computer through a motion control card in the computer and an amplifier. There is also a linear magnetic scale for each direction of the X-Y table, which measures the x or y positions. The output of the magnetic scales is fed into the computer.

Apart from interfacing the ADC card and motion control card, the computer has a software application installed. With the software application, an operator can select sampling parameters, such as the number of sampling points and the step length, and the number of sampling traces etc.

The procedure for operation of the laser profilometer is:

- Set up measuring parameters such as sampling numbers and resolutions of the X-Y table
- Put the sample in the position so that the laser spot is pointed to the centre of measured area
- Adjust the laser sensor height to make the laser spot focused
- Start measuring

Compared to conventional metal stylus profilometer such Talysurf, the laser profilometer of this kind are sometimes referred to as light stylus profilometer, as the measurement principles are the same, except using light, usually laser, as a stylus. Since the laser profilometer is based on a non-contact principle, it has a higher measuring speed. The normal measuring rate of the laser profilometer is 500 Hz. Suppose the step per measurement is 0.025 mm, then the measuring is 12.5 mm/sec. Compared to the measuring speeds of 0.2 mm/sec reported in [1] and 1.27 mm/sec in [16], the measuring speed of this laser profilometer is much higher. Also due to the non-contact principle, the laser profilometer introduces no deformation on the measured surface, which also means no deformation errors introduced in the measurement.
Perhaps surprisingly, however, non-contact systems are rarely more accurate than a good stylus-based contact instrument [97]. The laser spot of 2 \( \mu \text{m} \) is not necessarily smaller than contact stylus tip. There are even styli with tips as small as 2 \( \mu \text{m} \) (radius). Disadvantages of non-contact systems include not being able to measure into small bores or traverse across widely changing shapes as easily as a standard diamond stylus could do [97]. In addition, non-contact systems cannot ‘sweep aside’ dirt.

4.2 Average of multiple traces

Waviness on planed wood surfaces is mainly composed of cutter marks, and therefore it is directional, i.e. the waviness occurs along the feed direction. In contrast, roughness is more randomly distributed. On machined metal surfaces, roughness usually has smaller amplitude than waviness. However, due to the biological characteristics of wood, roughness can have larger amplitude than waviness after machining. For metal, a single trace may not be a precise representation of a surface, but the different between a single trace and average of multiple traces is very limited. As shown in Fig. 4-3, the solid line is an average of 20 traces of a steel surface, while the dotted line is a single trace. All the traces were measured with the laser profilometer. As seen in Fig. 4-3, the difference between the single trace and the average of 20 traces is only marginal.

In contrast, a comparison between a single trace and an average of multiple traces measured with the laser profilometer from a planed wood surface is shown in Fig. 4-4. The effect of averaging is significant. From a single trace, the basic shape of the wood sample can hardly be seen; while from an average of multiple traces, the cutter marks are very clear.

The reason why the single trace is so significantly different to the averaged trace is related to the biological nature of wood. As mentioned before, there are many ducts embedded in the body of wood. After being cut, the surface of wood appears to have many microscopic pores or canals. In addition, wood is anisotropic in nature. Therefore, the impact the cutter makes on the surface will not be constant. For example, some part of wood material may not be cut away, but torn away, as wood is full of fibers. All the pores, canals and torn surface features may appear distributed randomly from a single trace point of view, and roughness due to these features may have much larger amplitude than waviness amplitude. As a result, a single trace of wood surface may never reveal a clear waviness pattern. After averaging multiple traces of wood surface, however, randomly
distributed roughness components cancel out one another to some extent, making waviness components more distinct. But the waviness components have relatively smaller amplitude. The contrast between a single trace and an average of multiple traces is clearly shown in Fig. 4-4, where a single trace appears largely random in height with amplitude up to 100 µm, while an average of 100 traces has a clear waviness pattern and the amplitude is less than 30 µm.

In conclusion, for measuring machined wood surfaces with the laser profilometer, one single trace is far from reliable to represent the surface as a whole, especially from a perspective of waviness measurement. Then, here comes a question: how many traces are needed?

Fig. 4-3 Comparison of single trace and average of multiple traces from a steel surface
In principle, the more the number of traces to average, the more reliable the result will be. However, scanning of too many traces will be very time-consuming. Scanning of 200 traces with 800 sampling points in each trace will take the laser profilometer about 2 hours. Actually, there is only marginal difference between averages of traces when the number of traces is above a certain threshold. For the same wood sample shown in Fig 4-4, averages of 100 traces, 50 traces and 25 traces are compared and shown in Fig. 4-5. The difference is so small that the plots are largely overlapped. Therefore, scanning of 50 traces from a wood surface is normally implemented in this research.

As for the sample spacing, according to Nyquist sampling theory the sample spacing should be at least twice the minimum feature spacing. In practice, BS EN ISO 3274 1998 specifies that the minimum surface feature spacing is five times the data logging spacing. However, this guideline does not seem relevant in this case, as the main objective of this research is to find out information on waviness rather than roughness. Waviness, i.e. cutter marks, tested in this research is between 1 – 3 mm in width nominally. Therefore, the sample spacing does not need to be very small, say shorter than 10 µm. Furthermore, there is a limit of 800 for maximum number of sampling points. Too small sample spacing will inevitably result in short evaluation length. As a result, the sample spacing in
this research is set to be 50 μm for 3mm and 2.5 mm cutter mark samples, and 25 μm for 2 mm, 1.5 mm and 1 mm cutter mark samples.

![Graph showing comparison of averages of 100, 50, and 25 traces](image)

**Fig. 4-5 Comparison of averages of 100, 50 and 25 traces**

### 4.3 Surface analysis

The purpose of measuring waviness on wood surfaces is different from the purpose of measuring generic surface texture. For the latter, there is a set of ISO standards for measuring parameters such as evaluation length, sampling length, sample spacing, and profile filter cut-off, and so on. These ISO standards will be introduced and their relevance to the wood surface measurement will be discussed later. In addition, the result of a generic surface texture measurement is always a statistical number or a set of numbers, such as $R_a$, $R_q$ etc. However, for measuring wood surface waviness, statistical numbers are not appropriate. In contrast, surface profiles are more desirable, from which cutter mark patterns can be analysed, and further machining conditions can be inferred. Therefore, although some ISO standards are referenced, the measurement conducted in this chapter is not restricted to the ISO standards.

After averaging multiple profiles of a wood surface, a total profile is obtained for the surface. In here, the term *total profile* is used in accordance with BS EN ISO 3274:1998.
Also in accordance with the standard, nominal form removal is implemented by using best-fit least squares method. The nominal form is the intended underlying shape of the surface. The nominal form will be a straight line for a flat surface or an arc for a circular or spherical surface. Since the samples in this research are all flat boards in principle, the nominal form should be a straight line. However, it is very difficult, if not impossible, to guarantee that the sample surface is levelled perfectly. The reason that profiles shown in Fig 4-3, Fig. 4-4 and Fig. 4-5 are tilted is considered due to unleveling of the samples. One simple form of unleveling is that the surface to be measured is not parallel to the bottom surface of the sample. Consequently, nominal form removal is mainly for elimination of unleveling of the sample surface.

The best-fit least squares method is to find out a mean line running through the profile, where the square sum of the distances between every point on the profile and the corresponding points on the mean line is the least. As illustrated in Fig. 4-6, suppose $p_i$ is the distance between the point on the surface profile and the corresponding point on the least squares mean line, $1 \leq i \leq n$, then the least squares mean line satisfies the requirement $\sum_{i=1}^{n} p_i^2 \rightarrow \min$

According to BS EN ISO 3274:1998 [9], a profile filter, referred to as $\lambda_s$, is applied to the total profile after the nominal form removal. By BS EN ISO 4287:2000 [98], $\lambda_s$ profile filter is defined as filter which defines the intersection between the roughness and the even shorter wave components present in a surface. (See Fig. 4-7) The purpose of applying $\lambda_s$ profile filter is to eliminate the difference introduced by different stylus tip size and different sample spacing. Further recommended in the standard, the cut-off wavelength is standardised to be 2.5, 8, and 25 $\mu$m. The maximum stylus tip size and the maximum sample spacing are always smaller than the cut-off wavelength.
Recommendations made in BS EN ISO 3274·1998 and 4287:2000 are not appropriate in this research. On one hand, the maximum number of sampling points that the software accompanying the laser profilometer can support is 800 points. On the other hand, this research is pursuing as long evaluation length as possible. The laser spot, i.e. the ‘stylus tip’ in this profilometer is 2 μm. Only sample spacing can be selected. If sample spacing is set to be 8 μm, then the evaluation length will only be 6.4 mm at the most. In contrast, the evaluation lengths used in machine vision based methods in this research are 40 mm for coarse surfaces and 20 mm for fine surfaces. Accordingly, the sample spacing is set to be 50 μm for 40 mm evaluation length and 25 μm for 20 mm evaluation length. Therefore, no cut-off wavelength stated in BS EN ISO 3274.1998 is appropriate.

There is another reason for not applying λs profile filter to surface profiles measured with the laser profilometer. According to Fig. 4-7, the profile filter mainly benefits roughness analysis, as roughness profile is between λs and λc, which is defined as the intersection between the roughness and waviness components (BS EN ISO 4287 2000). Clearly, measurement with different stylus tip sizes and sample spacing will give different roughness results if λs profile filter is not applied. In this research, however, waviness is the only objective in surface analysis, so only a λc profile filter is necessary, and after application of λc filter, short wave components including those waves shorter than λs will also be filtered out.

Hence, selection of λc profile filter is the step immediately after removal of nominal form in this research. This includes selection of a proper filter type and a proper cut-off wavelength λc.
There are a number of filters for this purpose, such as Sliding Average filter, 2CR filter, and Gaussian filter etc. Among these filters, the Gaussian filter has good roll-off capability and introduces low distortion and phase shift to the data [97]. The rate at which the attenuation varies as the wavelength moves away from \( \lambda_c \) is known as 'roll-off' [97]. The Gaussian filter is also recommended in BS EN ISO 11562:1998 [99]. Actually abovementioned \( \lambda_s \) and \( \lambda_c \) profile filters and the following \( \lambda_r \) filter are all Gaussian filter in nature, but they have different cut-off wavelengths.

Essentially, the kernel of the Gaussian filter is a weighting function, which has the shape of a Gaussian density function (Fig. 4-8) and is mathematically described by the equation [99]

\[
s(x) = \frac{1}{\alpha \lambda_c} \exp \left[ -\pi \left( \frac{x}{\alpha \lambda_c} \right)^2 \right]
\]

Eq. 4-1

where \( \lambda_c \) is the cut-off wavelength of the filter, and \( \alpha \) is a constant, defined by

\[
\alpha = \sqrt{\frac{\log 2}{\pi}} = 0.4697
\]

Eq. 4-2

![Fig. 4-8 The kernel of Gaussian filter](image)

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Note that the Y-axis in Fig. 4-8 represents \( s(x) \cdot \lambda_c \) rather than \( s(x) \), and X-axis \( x/\lambda_c \) rather than \( x \). This makes Gaussian filters with different \( \lambda_c \) have the same scale on X-axis and Y-axis. This can be proved with the following derivation of Eq. 4-1.

\[
s(x) \cdot \lambda_c = \frac{1}{\alpha} \exp \left[ -\pi \left( \frac{x}{\alpha} \right)^2 \right]
\]

Eq. 4-3

and here

\[
x = \frac{x'}{\lambda_c}
\]

Eq. 4-4

where \( x' \) in Eq. 4-4 is equivalent to \( x \) in Eq. 4-1.

The area under a Gaussian filter kernel is always 1, i.e. sum of \( s(x) \) is always 1. This can be proved with the following derivation.

\[
\int_{-\infty}^{\infty} s(x) \, dx = \int_{-\infty}^{\infty} \frac{1}{\alpha \lambda_c} \exp \left[ -\pi \left( \frac{x}{\alpha \lambda_c} \right)^2 \right] \, dx
\]

\[
= \frac{1}{\alpha \lambda_c} \frac{\alpha \lambda_c}{\sqrt{\pi}} \int_{-\infty}^{\infty} \exp \left[ -\left( \frac{\sqrt{\pi} \cdot x}{\alpha \lambda_c} \right)^2 \right] \left( \frac{\sqrt{\pi} \cdot x}{\alpha \lambda_c} \right) \, dx
\]

\[
= \frac{1}{\alpha \lambda_c} \cdot \frac{\alpha \lambda_c}{\sqrt{\pi}} \cdot \sqrt{\pi}
\]

\[
= 1
\]

Eq. 4-5

Due to the value of \( \alpha \), the Gaussian filter is defined to have a transmission of about 50% (46.97% exactly to say) at the cut-off wavelength. This is why \( \lambda_c \), \( \lambda_c \) and \( \lambda_c \) in Fig 4-7 are all taken at 50% transmission.

Note that Eq. 4-1 is only a mathematical description for the Gaussian filter in a continuous way. In practice, a discrete version of the function has to be implemented, as the measured profile is a vector of equally spaced discrete points. Let \( x_k = k \Delta x \), then the discrete representation of the Gaussian filter is expressed as [99]

\[
s_k = \frac{\Delta x}{\alpha \lambda_c} \exp \left[ -\pi \left( \frac{k \Delta x}{\alpha \lambda_c} \right)^2 \right]
\]

Eq. 4-6

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where $\Delta x$ is the sample spacing with which the surface is measured.

Eq. 4-6 is only an approximation to Eq. 4-1. Clearly, the smaller the sample spacing $\Delta x$, smaller the error of the approximation. The error can be calculated with

$$\varepsilon = \left| 1 - \sum_i s_i \right|$$

Eq. 4-7

As expressed in Eq. 4-5, the area under a Gaussian filter kernel, i.e. the sum of the Gaussian filter kernel is always 1. That is where the number 1 in Eq. 4-7 comes from.

In order to determine $\lambda_c$, the standard BS EN ISO 3274:1998 was first referenced. However, the standard is found not to be helpful in this case, as $\lambda_c$, i.e. the nominal values of the cut-off wavelengths of the filter are recommended to be selected from the series

$$... \text{mm}; 0.08 \text{ mm}; 0.25 \text{ mm}; 0.8 \text{ mm}; 2.5 \text{ mm}; 8 \text{ mm}; ... \text{mm}$$

This series is clearly not appropriate for the surface analysis in this research.

Actually, there is a requirement for the selected $\lambda_c$. That is the selected $\lambda_c$ should ensure that after applying the $\lambda_c$ filter, the filtered profile is so smooth that there are only one peak and one valley in each period on the profile. Here the peak is referred to the local maximum in height and valley local minimum in height. By this way, cutter mark widths, i.e. peak-to-peak distances on the profile, can be measured reasonably.

After tests, it is found that when $\lambda_c$ is half of the nominal cutter mark width, the filtered profile can meet the requirement and still hold enough waviness information. Fig. 4-9 shows some transmission characteristics of typical $\lambda_c$ filters, which are half of nominal cutter mark widths tested throughout the research.
Note that in Fig. 4-7, BS EN ISO 4287 2000 also recommends a $\lambda_f$ filter, which defines the intersection between thewaviness and the even longer wave components present in the surface. This filter is mainly aimed to exclude form error from the waviness. However, this filter is not applied in the research. There are some reasons. Firstly, the ISO has not yet adopted a default relationship between $\lambda_c$ and $\lambda_f$ (BS EN ISO 4287:2000). Secondly, as pointed out in [99], 'such filters are seldom employed as use of even a moderate bandwidth (e.g. 100.1) is often impractical because of the evaluation length required'. Here 'such filters' are referred to $\lambda_f$ filters. The cutter mark widths tested in this research are between 1 - 3 mm Therefore the evaluation length of 100 - 300 mm will be required. (BS EN ISO 4287:2000 does not give default evaluation length for w-parameters.) The maximum sampling number supported by the profilometer is 800 points. If the sample spacing is 50 $\mu$m, the evaluation length is only 40 mm, far less than the required length. If increasing the sample spacing, too much information will be lost. The last not the least, the measurement with the profilometer is only used as a reference to compare with measurements with machine vision-based methods such as the Light Sectioning method and the Photometric Stereo method. These methods also require profile filters. So long as the filters applied to the profiles derived from all methods have
the same transmission characteristic and the same cut-off wavelength, the results are comparable.

4.4 Problems with operating the laser profilometer

Two problems with operating the laser profilometer have been looked into, which are:

- Repeatability of the X-Y table
- Misalignment of the sample relative to the scanning direction

4.4.1 Problem with the repeatability of the X-Y table

The driving mechanism of the X-Y table is made of step motors and ball screw slides. Magnetic scales are mounted on the slides. So, the actual position of the X-Y table for every reading of the laser head is available. After examining the raw data from the profilometer, it is found that the actual X-axis positions of the sampling points are not always at the nominal positions. This is acceptable provided the errors do not exceed a certain level, such as the sample spacing. For a single trace, this is not a problem. For averaging multiple traces, however, this may present a problem. The sampling points of multiple traces in the sampling point matrix are not aligned. As mentioned in Section 4.2, averaging multiple traces are necessary to analyze the waviness profile on wood surfaces. Clearly, misaligned sampling points among traces will distort the averaged profile in theory. The key question is to what extent the distortion can be.

In order to study the X-axis repeatability of the X-Y table, 100 traces were taken from a wood sample. The test is schematically illustrated in Fig. 4-10. As seen in Fig. 4-10, there are 800 sampling points on each of the 100 traces. The sample spacing is 25 μm in X direction and 20 μm in Y direction. In this test, the height readings of the laser profilometer do not matter. Nor do the y-positions of the sampling points. Only the x-positions of the sampling points need to be studied.
After 100 traces were taken, x-positions of the first sampling points of the 100 traces were picked out and compared in Fig. 4-11. The X-axis is the trace number from 1 to 100, and the Y-axis is the x-position of the first sampling point of the 100 traces. Note that the value ‘0’ on Y-axis is the average of x-positions of the first sampling points of these 100 traces. From Fig. 4-11, it can be seen that x-positions of the first sampling points of the 100 traces vary in a range of about 25 μm. This is remarkable when compared to the sample spacing of 25 μm.
The x-positions of the 400th sampling points on the 100 traces relative to their average are also studied. As seen in Fig. 4-12, the x-positions of the 400th sampling points of the 100 traces vary in a much smaller range than the first sampling points, only about 6 μm.

The reason why the first points have a larger varying range in x-position is because of backlash of the X-Y table in X direction. After taking the 800th sample in one trace, the X-Y table will move rapidly back to the position of the first sampling point, then move one step in Y direction, and then starts the next trace. Therefore, backlash of the X-Y table in X direction has a major influence on the first sampling points varying in x-position over a relative larger range.

![Fig. 4-12 Positions of the 400th sampling points on 100 traces relative to the average](image)

In order to show the repeatability at each of the 800 sampling points over the 100 traces, x-position varying range of each of the 800 sampling points is plotted in Fig. 4-13. The X-axis is the sampling point number, ranging from 1 to 800. The Y-axis is the repeatability. The repeatability at ith sampling point is the x-position varying range of the 100 traces at their ith sampling point. From Fig. 4-13, it can be seen that in the first half of the measurement (before the 400th sampling point), except the first 10 or so points, the repeatability is about 5 μm; while in the second half of the measurement the repeatability is about 22.5 μm with some even exceeding 25 μm, which is the sample spacing.

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However, the pattern of small repeatability first and then large repeatability is not a repeated characteristic of the X-Y table. In another measurement shown in Fig. 4-14, the repeatability shows no regulation at all. This time, 40 traces with sample spacing of 50 μm are studied. The average repeatability over the 800 sampling points is 16 μm.
In conclusion, the repeatability of the X-Y table does not have a fixed pattern, and it can be as large as the sample spacing. Poor repeatability of the X-Y table will cause sampling points misaligned among traces, which may eventually affect the averaging algorithm discussed in Section 4.2.

In order to eliminate the negative effect of misaligned sampling points among traces, the raw data are resampled and aligned before averaging. The resampling is done by using interpolation with sample spacing of 1 μm so that alignment of sampling points on the traces is easy to implement. After resampling, all sampling points on the traces are aligned according to their x-positions. After that, the traces are averaged as described in Section 4.2.

After implementing the resampling and alignment algorithm, however, it is found that the difference that the algorithm can make to the final averaged profile is only marginal. Fig. 4-15 shows a comparison between a resampled-aligned-averaged profile vs its corresponding only-averaged profile. As seen in the figure, these two profiles almost overlap. More comparisons show the same result. Therefore, it is concluded that the poor repeatability of the X-Y table does not affect the averaging algorithm too much, and the resampling and alignment algorithm is not necessary.

![Fig. 4-15 Comparison of resampled profile and non-resampled profile](image-url)
This research identified the problem of X-axis repeatability associated with the X-Y table of the laser profilometer, and proved that the problem does not affect the data analysis algorithm of averaging multiple traces. With respect to the sources of error for the X-axis repeatability of the X-Y table, in addition to the abovementioned backlash issue, there might be some other reasons, such as the accuracy and repeatability of the step motor and the accuracy and repeatability of the ball screw slide. However, investigation of the sources of error is considered out of the scope of the research. Therefore, no further studies have been conducted in this direction. This may be studied in the future for the purpose of improving the laser profilometer.

4.4.2 Misalignment of the sample relative to the scanning direction

There is another problem with averaging multiple traces measured with the profilometer. Since cutter marks on a wood surface are directional, if the sample is misaligned relative to the scanning direction as shown in Fig. 4-16, the averaging algorithm may give distorted profiles. In Fig. 4-16, the arrowed line is the X-axis of the X-Y table, i.e. the scanning direction; the dotted lines are the peaks of cutter marks on an ideally aligned surface, i.e. the cutter marks being perpendicular to the X-axis; the solid lines are the peaks of cutter marks on a misaligned surface. The angle \( \theta \) is referred to as the angle of misalignment.

![Fig. 4-16 Misalignment of sample relative to scan axis](image)

Fig. 4-16 shows how the sample is aligned in the experiment. As seen in Fig. 4-16, there is an edge on the sample surface, which is machined in the same process as the surface. Therefore, alignment of the surface can be implemented by alignment of the edge to the X-axis of the X-Y table. However, the profilometer does not provide any alignment mechanism, which makes it very difficult to align the edge relative to the X-axis of the X-
Y table to a high accurate level. It can be assumed that there is always a certain degree of misalignment of the sample incurred. Consequently, study of the effects of misalignment on the algorithm of averaging multiple traces is necessary.

Fig. 4-17 Illustration of how samples are aligned

The effects of misalignment of samples are simulated with the following conditions:

1. The radius of cutter is 60 mm
2. The cutter mark width is 2 mm
3. Evaluation length (X-axis) is 40 mm with 1 μm sample spacing
4. Evaluation width (Y-axis) is 5 mm with 200 μm sample spacing
5. The angles of misalignment are in range 0° - 10°

Fig. 4-18 shows the surface profiles with no misalignment and 10° misalignment. It can be seen that the profile from the misaligned sample after averaging traces has smaller amplitude and a phase shift. However, the simulation also shows the periods of the two profiles are the same. After multiplying the amplitude of the profile simulated with 10° misalignment (dashed line in Fig. 4-18) by a factor and shifting the profile properly, the modified profile becomes identical with the profile simulated with no misalignment (solid line in Fig. 4-18).
Fig. 4-18 Simulation of $10^\circ$ misalignment

More simulations with different angles of misalignment give the same result. Fig 4-19 shows the relationship between the amplitude and the angle of misalignment, while Fig. 4-20 shows the relationship between the phase shift and the angle of misalignment. Note that amplitude values in Fig. 4-19 are all calculated relative to the amplitude when there is no misalignment. As seen in the figures, the relationships are all linear, with amplitude being inversely proportional to the angle of misalignment and phase shift proportional to the angle of misalignment.

In conclusion, when the sample is misaligned relative to the scanning direction, the averaged profile will have distorted (smaller) amplitude, and a phase shift from the actual profile. However, the shape of the surface profile will remain. This is very important because when the profile measured with the laser profilometer is compared to profiles measured with the methods investigated in the following chapters, relative amplitude of profiles will be used and profiles may also be phase-shifted. All these make shape of profile the only thing that matters. This will be further discussed in the following chapters.
Fig. 4-19 Amplitude vs. angle of misalignment

Fig. 4-20 Phase shift vs. angle of misalignment
5. The Light Sectioning method

The Light Sectioning method has been briefly introduced in Chapter 2. The method will be further discussed in depth in this chapter. The outline of this chapter is as follows.

- Geometric model of the Light Sectioning method
- Experimental work
- Image analysis
- Comparison with the laser profile
- Discussion on misalignment in the Light Sectioning method
- Differential Light Sectioning method
- Limitations of the Light Sectioning method
- Conclusions

5.1 Geometric model of the Light Sectioning method

The principles of the Light Sectioning method have been descriptively introduced in Chapter 2. In this section, a mathematical description of the Light Sectioning method is given.

Fig. 5-1 shows a 3-D geometric model of the Light Sectioning method. As seen in the model, the cutter marks on the surface are formed parallel to the X-axis, and the ridges of the cutter marks are parallel to the Y-axis. A laser plane, perpendicular to the Y-Z plane, and at a small angle to the X-Y plane, is projected from the side of the surface. The laser plane intersects with the surface, forming a light section.

For simplicity, the cutter marks are modelled as circular arcs with R as their radius, which is also the cutting radius of the cutter. In fact, as described in Appendix A, the cutter mark is not in the waveform of circular arc, but trochoid [1, 3, 4, 96]. However, according to Hynek's research [96], there is no width difference between the circular arc and the trochoid; and the height difference between the circular arc and the trochoid is very small, typically less than 5% of the actual surface height. In addition, the geometric model in Fig. 5-1 is only meant to help understand the Light Sectioning method. Thus, circular arc is used as an approximation to the actual cutter mark waveform in this chapter.
Since the cutter marks in Fig. 5-1 are formed parallel to the X-axis and their ridges are perpendicular to the Y-axis, the side view of the cutter marks on the X-Z plane is a circular arc, as shown in Fig. 5-2. Mathematical description of the circular arc is

\[ x^2 + (z - z_0)^2 = R^2 \]

Eq. 5-1

where \( R \) is the radius, \( (0, z_0) \) is the circle centre, \(-w/2 \leq x \leq w/2\), and \( w \) is the cutter mark width. The side view of the light section on the X-Z plane overlaps the circular arc, and the side view of the laser plane on the X-Z plane overlaps the X-Z plane itself.

\[ w = \text{width of cutter mark} \]

Fig. 5-2 X-Z plane of the Light Sectioning model
The side view of the cutter mark on the Y-Z plane is two horizontal lines, as shown in Fig. 5-3. The solid line stands for the ridge of the cutter mark; while the dashed line stands for the valley of the cutter mark. The distance between the two lines is the depth of the cutter mark. In addition, the laser plane becomes an oblique line on the Y-Z plane, which is described as
\[ z = k \cdot y. \]

Eq. 5-2

Since the angle of the laser plane with respect to the X-Y plane is normally very small, the value of \( k \) is close to 0. Clearly, \( k \) is a negative value in the coordinate system shown in Fig. 5-3.

Fig. 5-3 Y-Z plane of the Light Sectioning model

On the X-Y plane in the Light Sectioning model, the light section will be viewed as a waveform. Actually, the X-Y plane is also the imaging plane.

From Eq. 5-1 and Eq. 5-2, Eq. 5-3 can be derived, and then Eq. 5-4 can be achieved
\[ x^2 + (k \cdot y - z_0)^2 = R^2 \]

Eq. 5-3

\[ \frac{x^2}{R^2} + \left( \frac{y - z_0}{k} \right)^2 = 1 \]

Eq. 5-4

According to Eq. 5-4, the light section is part of an ellipse, with \((0, z_0/k)\) as its centre and \(R\) as its semiminor axis and \(R/k\) as its semimajor axis. The ellipse is illustrated in Fig 5-4.

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On the X-Y plane, the starting point and the ending point of the light section are also \((-w/2, 0)\) and \((w/2, 0)\).

Substitute \(x = 0\) for \(x\) in Eq. 5-4 to derive \(y\).

\[
y_{x=0} = - \frac{R - z_0}{k} = - \frac{h}{k}
\]

\[\text{Eq. 5-5}\]

Therefore, the apex of the light section arc on the X-Y plane is \((0, -h/k)\). Note that \(k < 0\) and \(h > 0\), so \(-h/k > 0\).

There is an assumption for the above analysis, which is that cutter mark surface heights vary only along the X-axis. In reality, however, this assumption is not always the case. Surface heights of cutter marks on wood surfaces can vary along the Y-axis as well. The Y-axis surface height variation makes the real situation much more complicated. This issue will be discussed in Section 5.7.

### 5.2 Experimental work

According to the principles of the Light Sectioning method discussed in Section 5.1 and in Chapter 2, a test rig was constructed as shown in Fig. 5-5. A laser projects light in a fan from the side of the wood sample, which makes a light section on the sample surface. The light section, along the feed direction on the wood surface, i.e., X-axis direction in Fig. 5-1, is captured by a camera, which connects to a computer.
source, the camera, and other important components in the test rig are discussed in detail in Chapter 3.

![Test rig for the Light Sectioning method](image)

The laser is mounted on a goniometer so that the angle of incidence of the laser light can be adjusted. Due to the triangular relationship shown in Fig. 2-14, this angle of incidence has a magnifying effect on the heights of the waves of the light section. The smaller the angle, the more distinguishable the magnifying effect of the Light Sectioning. However, if the angle is too small, the projected light will spread over a wide range on the surface, consequently making the light section appear broken. Fig. 5-6 is such an example for light sections with a too small angle of incidence, which is slightly smaller than 1°. Note that the image in Fig. 5-6 has had the top and the bottom areas of the image truncated, as the useful information is mainly in the middle of the image. The original FOV of the image is 30x24 mm, while the truncated FOV is about 30x10.8 mm. As seen in Fig. 5-6, it is difficult to extract a light section from the image, as the light-section-extracting algorithm relies on clear light section images like the one shown in Fig. 5-7.
Fig. 5-6 A light section with too small angle of incidence

Through experiments, it is found that the angle of incidence should not be smaller than 1.5°. However, when the angle is greater than 6°, the magnification of Light Sectioning is less than 10x, which is considered not large enough to get satisfactory results. Therefore, the angle between the incident laser beam and the surface to be tested is restricted to the range 1.5° to 6°.

A number of images were taken with the test rig described above; one of these images is shown in Fig. 5-7. In Fig. 5-7, the waviness of the light section is even discernible to the eye. Note that the image in Fig. 5-7 is only the useful portion of the original image, with those regions only in black removed so that the image is not in the aspect ratio of 5 to 4. If in a practical project, the action of focusing on the useful part of the image can be implemented by defining the Region of Interest (ROI) in the camera's configuration. This can also increase the frame rate. More information about the camera is referred to Chapter 3.

Fig. 5-7 A light section

Conditions under which the image in Fig. 5-7 was taken are as follows:

- Field of View (original): about 40 x 32 mm
- Image resolution (original): 1280 x 1024
5.3 Image analysis

5.3.1 Noise removal

Noise in an image usually results from the camera itself. This type of noise normally has a fixed pattern. In order to eliminate the noise of this type, a reference image can be taken with the lens closed, therefore producing a ‘pure black’ image. Actually the ‘pure black’ image is not really pure black, but contains the fixed pattern noise of the camera. Subtracting the ‘pure black’ image from the meaningful image removes the noise.

Accordingly, a reference image was taken with the same camera as the image in Fig. 5-7 was taken with. Since the reference image is nearly a pure black image, it is not shown here. Then a new image was obtained by subtracting the reference image from the original image in Fig. 5-7, and is shown in Fig. 5-8. Almost no discernable difference can be perceived by visual comparison of the two images. The correlation coefficient between these two images is 0.9999. So this noise removal operation is not really necessary.

![Image after noise removed](image.png)

5.3.2 Profile extraction algorithm

In order to extract a profile from the light section, the edges of the light section have to be established. This involves edge detection techniques. In the next paragraphs, some generic edge detection algorithms will be introduced, which prove not suitable for the
Edge detection in this particular case. After that, a specific edge detection algorithm will be discussed.

Edges in an image are nothing but sharp variations of the grey values in the image [100]. Therefore, the aim of edge detection is to locate the sharp variations of grey values in the image. In order to achieve this aim, two basic approaches can be applied: gradient-based edge detection and edge detection by zero crossings. The first one is to search for edges with the first derivative of grey values, while the second one is to search for edges with second derivative of grey values. There is a very good illustration for these two approaches in Fig. 5-9.

![Fig. 5-9 Noisy 1-D edge and its first derivative and second derivative [101]](image)

In Fig. 5-9, the x-axes in three graphs all stand for pixel positions. Graph a is an intensity profile in relative grey values with 1 being the brightest and 0 the darkest. Graph b is the first derivative of the intensity profile in Graph a. Graph c is the second derivative of the intensity profile.

As seen in Fig. 5-9, edges occur at the sharp slopes on the intensity profile, and at the spikes on the first derivative, and at the points where the second derivative crosses zero. However, not every zero crossing on the second derivative indicates an edge. Only zero crossings with preceding and following peaks significantly higher than the average indicate edges.
Based upon the above basic principles and with some efforts to optimise the edge detection procedure, a number of edge detection algorithms are available to choose, such as Sobel method, Prewitt method, Roberts method, Laplacian of Gaussian method, zero-cross method, and Canny method etc [102].

The first three methods are gradient-based algorithms, which find edges at those points where maximum gradient occurs. The Laplacian of Gaussian method and zero-cross method are based on zero crossing of second derivative of grey values. The Canny method also uses the first derivative, but it smooths the image with a Gaussian filter before applying the first derivative operator. Canny method is recommended as the most powerful edge detection method in MATLAB Image Processing Toolbox. The method differentiates strong edges from weak edges, and only includes the weak edges in the output if they are connected to strong edges; it is therefore less likely to be ‘fooled’ by noise and more likely to detect true weak edges.

In order to test the effectiveness of the abovementioned edge detection algorithms on the light section image in Fig. 5-8, these algorithms were implemented on the image in MATLAB, and Fig. 5-10 to Fig. 5-15 are the results respectively.

![Fig. 5-10 Sobel method](image1)

![Fig. 5-11 Prewitt method](image2)
Fig. 5-12 Roberts method

Fig. 5-13 Laplacian of Gaussian method

Fig. 5-14 Zero-cross method

Fig. 5-15 Canny method
From these figures it can be seen that gradient-based methods, including Sobel method, Prewitt method, and Roberts method, perform better than zero crossing methods such as Laplacian of Gaussian method and Zero-cross method, and Canny method in this particular case in terms of extracting useful edges. Although customising some input arguments of these edge detection algorithms may improve the results, there is a fundamental problem with the methods. That is that these generic edge detection methods always try to find all the edges that meet the detection criteria. As a result, many useless edges are picked up. This problem is particularly shown in Fig. 5-13 to Fig. 5-15.

The objective of edge detection in this case is to establish top edge and bottom edge for the light section. This can be achieved by taking advantage of the characteristics of the light section image, which is with a bright foreground on a nearly black background. The edges are boundaries dividing the foreground and background.

Fig. 5-16 shows the intensity profile across the 640th column of the image, which is located in the middle of the image, as shown in Fig. 5-17. It can be found that the intensity profile has steep slopes at both sides of the light section, and has a ‘flat top’ in the middle. The ‘flat top’ is due to the limited dynamic range of the camera, however, it can be used to detect the edges.

![Intensity profile across the 640th column](image)

Fig. 5-16 Intensity profile with a ‘flat top’
The edge detection strategy is to locate the row numbers of the points a and b in Fig. 5-16, which are the left corner and the right corner of the 'flat top' respectively, and do this operation column by column across the image from the first column to the last one. Then, linking all the left corner points gives the top edge, and linking all the right corner points gives the bottom edge. Finally, the light section profile is obtained by averaging the top edge and the bottom edge. Accordingly, the profile extraction algorithm is composed of three sub-algorithms: one for detecting top edge, one for detecting bottom edge, the last one for averaging.

For the top edge detecting and bottom edge detecting, there is a situation that needs considering. As shown in Fig. 5-18, on the 665th column in Fig. 5-17, the top edge point is a1 according to the edge detection strategy. But this point is suspicious, because there is a gap between a1 and a2. After checking the image in Fig. 5-17, it is found that a1 is a false edge point (circled and arrowed in Fig. 5-17). The real edge point for this column should be at a2. This example occurs in the top edge detection, but this situation could occur in the bottom edge detection as well. In order to deal with this issue, the edge detection sub-algorithms first establish a detection zone for the top edge or the bottom edge, in which only real edge points could fall, and then locate the edge points. The top edge detection sub-algorithm is illustrated in Fig. 5-19.
Establish an initial edge by locating the first point that is 255 in grayscale value in every column and then linking all such points together.

Calculate the least squares mean line (ls) of the initial edge and the standard deviation (std) relative to the least squares mean line ls.

Set up a zone with the range [ls-c*std ls+c*std].

Estimate a zone with the range of [ls-c*std ls+c*std].

According to the profile extraction algorithm, the top edge and the bottom edge, and the average of the edges, i.e., the light section profile, are established. The edges and the light section profile are plotted together in Fig. 5-20. Note that in Fig. 5-20, the origin of Y-axis is at the upper left corner (not shown in the figure), as by this way, the profiles in Fig. 5-20 match the image in Fig. 5-8.
In order to compare the edges and the light section profile with the light section, the edges and the light section profile are superimposed onto the original image and the resultant image is shown in Fig. 5-21. As seen in the figure, the detected edges largely coincide with the edges of the light section.

**Fig. 5-20 Edges and the light section profile**

In Fig. 5-20, the light section profile (the middle curve) encompasses high frequency components and low frequency components. The high frequency components are associated with the surface roughness, although the association is not that exclusive. However, the low frequency components are primarily associated with the surface roughness.
waviness and surface form if there is any. Therefore, in order to extract the surface waviness from the profile, a low-pass filter needs to be applied.

There are many low-pass filtering algorithms to choose. Savitzky-Golay filter and polynomial best-fit algorithm have been tried. They both work well. However, in order for the result to be comparable with the result from the laser profilometer, Gaussian filter was selected. The reason why the Gaussian filter was selected, and detailed descriptions of the Gaussian filter has been given in Chapter 4. The cut-off wavelength for the Gaussian filter is about 1.5 mm, and the cutter marks made on the surface for Fig. 5-8 are about 3 mm in width. When the cut-off wavelength is far less than 1.5 mm, the smoothing effect of the filter is not good enough, which makes the following peak location operation difficult. After filtering, the resultant profile of the light section is plotted in Fig. 5-22. Note that the least squares mean line of the profile has been removed. This is in order for the light section profile to be comparable with the laser profile, which has the least squares mean line removed. In addition, the smoothed light section is shorter than the original section. This is because the Gaussian filter is essentially an averaging filter that makes the first small portion and the last small portion of the smoothed profile distorted. The width of the small portions is half of the width of the filter kernel. In addition, the numbers 1 and 23 in Fig. 5-22 indicate the first and the last turning points on the plot. The portion of the plot between marks 1 and 23 will be compared to the corresponding portion in Fig. 5-24.
5.3.4 Peak location

In order to measure the widths and heights of the cutter marks in the light section, the local maxima and the local minima on the profile in Fig. 5-22 need to be located. A peak location algorithm was therefore developed. Since the profile is already adequately smoothed, the algorithm is simply locating all the turning points on the plot. Although it is named peak location algorithm, it is actually able to locate both the local maxima and the local minima.

5.4 Comparison with the laser profile

In order to assess the performance of the Light Sectioning method, the laser profilometer described in Chapter 4 was used as a reference.

On the same area of the wood surface as the light section was taken from, a surface profile was obtained with the laser profilometer and is shown in Fig. 5-23. On the sample surface, pencil marks were made so that it is easy to make the laser profile cover the same area as the light section profile, with the difference between the profiles not more than half of a cutter mark width, which is about 1.5 mm.
Similarly, the profile has had least squares mean line removed. After applying a Gaussian filter with the same cut-off wavelength of 1.5 mm, a smoothed profile is obtained and shown in Fig 5-24. The smoothed profile is also shorter than the original profile because of the same reason as mentioned with the light section profile. With the same peak location algorithm, the local maxima and minima are located and marked on the smoothed profile.
So far, the locations of the local maxima and minima on the light section profile and the laser profile are known. From these, the widths and the heights of the waviness profile can be calculated and compared. For the laser profile, the calculation is simple and straightforward, as the coordinate values of the local maxima and minima are in micrometers. As for the light section profile, however, the coordinate values of the local maxima and minima are in pixels. Therefore, calibration of the FOV of the image is necessary. Calibration of FOV of images is discussed in Chapter 3. For the image in Fig. 5-7, the horizontal length is calibrated to be 40.256 mm. Equally important, the angle of incidence of the laser beam needs to be calibrated so that the surface heights can be calculated.

Compared to the calibration of field of view, calibration of the angle of incidence at a certain degree of accuracy is very difficult. Even to simply measure the angle is difficult. Although the goniometer can be calibrated, the calibration is only for the angles between the laser housing and the light source stand base plane (See Chapter 3, Fig. 3-1 and Fig 3-2). It is difficult, however, to exactly know the angle between the light source stand base plane and the wood surface plane. If taking the misalignment of the laser beam and the laser housing, and wood warp into account, the situation becomes more complicated.
In addition to the difficulty of calibrating the angle of incidence, the surface profile from the laser profilometer should by no means be considered absolutely accurate. The raw data from the laser profilometer are representatives of whole surface texture including from very low frequency form to medium frequency waviness and to high frequency roughness. These data need filtering to extract the waviness portions of surface texture. Filtering is an indeterministic procedure. The result of filtering could be different from one type of filter to another, especially in terms of amplitudes of the filtered signal. Therefore, the waviness profile obtained from the laser profilometer should not be seen as reliable as a thickness of a part measured with a micrometer.

Due to the above reasons, another approach was taken to bypass the awkwardness of calibration of the angle and the uncertainty of the laser profilometer method. The purpose of calibration is to establish the linear relationship between the values in pixel and values in a metric unit. Since the relationship is assumed linear, the ratio of values in pixel to values in a metric unit must be closely around a fixed number. Accordingly, the ratios of surface waveform widths and heights from the light section profile and the laser profile were calculated. In addition, the correlation between the light section profile and the laser profile is calculated for the purpose of comparison.

Therefore, the procedure for the comparison of the light section profile and the laser profile is as follows, with \( p_g \) standing for the light section profile and \( z_g \) standing for the laser profile.

1. Truncate \( p_g \) between points 1 and 23 in Fig. 5-22, and truncate \( z_g \) between points 1 and 23 in Fig. 5-24;
2. \( p_g = p_g - \text{mean}(p_g) \), \( z_g = z_g - \text{mean}(z_g) \),
3. \( p_g = -p_g / \text{range}(p_g) \), \( z_g = z_g / \text{range}(z_g) \);
4. Resample \( p_g \) with the sampling rate of \( z_g \);
5. Plot \( p_g \) and \( z_g \) together in Fig. 5-25.

Step 1 in the procedure is to align the two profiles with the assumption that points 1 and 23 in Fig. 5-22 and points 1 and 23 in Fig. 5-24 cover the same sample length. Steps 2 and 3 are to change the amplitude of the profiles so that they are comparable in Y-axis. The result of Steps 2 and 3 is the relative height, i.e., the ratio of real height to the range of the profiles. Note that in Step 3, there is a negative sign in \( p_g = -p_g / \text{range}(p_g) \). That is because the light section profile in Fig. 5-22 has its Y-axis origin at the upper left corner,
while the laser profile in Fig 5-24 has its Y-axis origin at the lower left corner. Step 4 is to resample the Light Sectioning profile, making it have the same number of sampling points in X-axis as the laser profile. This operation makes these two profiles comparable in X-axis, and the two profiles are both in metric unit. Finally, the light section profile and the laser profile are plotted in Fig. 5-25.

Firstly, the two profiles are compared in correlation coefficient. The correlation coefficient is calculated with MATLAB function corr2, which uses

$$\text{corr2}(A, B) = \frac{\sum_{m} \sum_{n} (A_{mn} - \bar{A})(B_{mn} - \bar{B})}{\sqrt{\left(\sum_{m} \sum_{n} (A_{mn} - \bar{A})^2\right)\left(\sum_{m} \sum_{n} (B_{mn} - \bar{B})^2\right)}}$$

Eq. 5-6

where $\bar{A} = \frac{\sum_{m} \sum_{n} A_{mn}}{m \times n}$ and $\bar{B} = \frac{\sum_{m} \sum_{n} B_{mn}}{m \times n}$. Note that $A$ and $B$ in Eq. 1-6 can be matrices or vectors. Here, $A$ and $B$ are vectors for the Light Section profile and the laser profile respectively, and their correlation coefficient is approximately 0.88.

![Fig. 5-25 Comparison of light section profile and laser profile](image)

Secondly, the widths and heights of waveforms on these two profiles are compared. The comparisons are shown in Table 5-1 and Table 5-2. The widths are the X-axis
distances in millimetres between the peaks on the profiles, while the heights are Y-axis distances between neighbouring points, i.e. peak-to-valley or valley-to-peak distances. Note that the heights are relative heights.

Table 5-1 Width comparison

<table>
<thead>
<tr>
<th>Width from the light section profile (mm)</th>
<th>Width from the laser profile (mm)</th>
<th>Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.11</td>
<td>3.25</td>
<td>0.96</td>
</tr>
<tr>
<td>2.70</td>
<td>2.52</td>
<td>1.07</td>
</tr>
<tr>
<td>2.95</td>
<td>2.88</td>
<td>1.03</td>
</tr>
<tr>
<td>4.10</td>
<td>3.67</td>
<td>1.12</td>
</tr>
<tr>
<td>2.64</td>
<td>2.99</td>
<td>0.88</td>
</tr>
<tr>
<td>2.64</td>
<td>2.83</td>
<td>0.93</td>
</tr>
<tr>
<td>3.05</td>
<td>2.89</td>
<td>1.05</td>
</tr>
<tr>
<td>3.30</td>
<td>3.44</td>
<td>0.96</td>
</tr>
<tr>
<td>3.34</td>
<td>3.04</td>
<td>1.10</td>
</tr>
<tr>
<td>2.48</td>
<td>2.61</td>
<td>0.95</td>
</tr>
<tr>
<td>2.99</td>
<td>3.16</td>
<td>0.94</td>
</tr>
</tbody>
</table>

Table 5-2 Height comparison

<table>
<thead>
<tr>
<th>Relative height From the light section</th>
<th>Relative height From the laser profile</th>
<th>Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.20</td>
<td>0.32</td>
<td>0.62</td>
</tr>
<tr>
<td>0.49</td>
<td>0.52</td>
<td>0.93</td>
</tr>
<tr>
<td>0.20</td>
<td>0.18</td>
<td>1.16</td>
</tr>
<tr>
<td>0.19</td>
<td>0.21</td>
<td>0.91</td>
</tr>
<tr>
<td>0.45</td>
<td>0.45</td>
<td>0.99</td>
</tr>
<tr>
<td>0.10</td>
<td>0.22</td>
<td>0.44</td>
</tr>
<tr>
<td>0.64</td>
<td>0.50</td>
<td>1.26</td>
</tr>
<tr>
<td>0.64</td>
<td>0.54</td>
<td>1.19</td>
</tr>
<tr>
<td>0.18</td>
<td>0.30</td>
<td>0.59</td>
</tr>
<tr>
<td>0.42</td>
<td>0.45</td>
<td>0.95</td>
</tr>
<tr>
<td>0.38</td>
<td>0.48</td>
<td>0.79</td>
</tr>
<tr>
<td>0.27</td>
<td>0.45</td>
<td>0.59</td>
</tr>
<tr>
<td>0.38</td>
<td>0.57</td>
<td>0.67</td>
</tr>
</tbody>
</table>
From Table 5-1, it can be seen that the widths measured from the Light Sectioning profile are largely close to the widths from the laser profile. The ratios of the widths are around 1. Fig 5-26 shows the distribution of the width ratios, with X-axis being the positions of the widths and Y-axis being the ratios. There are 11 widths measured. The mean value of the ratios is 1, and the standard deviation is 0.08.

<table>
<thead>
<tr>
<th>Width Ratio</th>
<th>Light Sectioning</th>
<th>Laser Profile</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.27</td>
<td>0.39</td>
<td>0.69</td>
</tr>
<tr>
<td>0.47</td>
<td>0.65</td>
<td>0.72</td>
</tr>
<tr>
<td>0.56</td>
<td>0.69</td>
<td>0.82</td>
</tr>
<tr>
<td>0.35</td>
<td>0.41</td>
<td>0.84</td>
</tr>
<tr>
<td>0.57</td>
<td>0.73</td>
<td>0.78</td>
</tr>
<tr>
<td>0.26</td>
<td>0.34</td>
<td>0.78</td>
</tr>
<tr>
<td>0.20</td>
<td>0.28</td>
<td>0.72</td>
</tr>
<tr>
<td>0.53</td>
<td>0.71</td>
<td>0.74</td>
</tr>
<tr>
<td>0.30</td>
<td>0.49</td>
<td>0.61</td>
</tr>
</tbody>
</table>

Fig. 5-26 Width ratios of the light section profile and the laser profile

However, the heights obtained from the two profiles, as shown in Table 5-2, are not in good accordance. The height ratios span a large range from about 0.4 to 1.3, as shown...
The mean value of ratios is 0.81, and the standard deviation is 0.21. The mean value does not matter, but the standard deviation does.

Compared to widths, heights obtained from these two profiles do not match very well. The first reason is that the waviness heights are in order of micrometers while waviness widths are in order of millimetres. Therefore, a minor deviation in the measurement and subsequent height calculations can produce a big difference. Another important reason is that the surface heights do not only vary along the feed direction but also vary along the direction perpendicular to the feed, i.e., the surface height variations occur along both X-axis and Y-axis in the geometric model in Fig. 5-1. Clearly, the latter type of height variations could also contribute to the light section created on the surface to some extent. If the height variations of this type are larger than or close to the height variations along the feed direction, the performance of the Light Sectioning method will be compromised. This issue will be further discussed later in this chapter.

5.5 Discussion on misalignment in the Light Sectioning method

In the experimental setup shown in Fig. 5-5, the laser stripe is supposed to be projected parallel to the feed direction. In reality, however, it is impossible to guarantee this setup. If the light stripe is not projected parallel to the feed direction, the light section
will appear inclined in the image, as illustrated in Fig. 5-28 (b). Fig. 5-28 (a) shows a perfectly aligned light section. The vertical lines in Fig. 5-28 represent the peaks of the cutter marks on the surface. (Here and in the following text, the camera is assumed to be aligned to the surface, i.e., the feed direction of the surface is parallel to one edge of the field of view of the camera.) Nevertheless, the inclination can be eliminated by removal of the least squares mean line of the light section. Just out of this consideration, the light section profiles in the previous figures all have the least squares mean line removed.

**Fig. 5-28 Misalignment of the light section**

In order to further study the effects of misalignment of light sections, a misaligned light section was simulated. In Fig 5-29 (a), a cutter mark wave in a light section with 5° of misalignment is plotted (dashed line) alongside the cutter mark wave with the least squares removed (solid line). In Fig 5-29 (b), the same cutter mark wave in the same light section with no misalignment is plotted. The simulated cutter mark is 2 mm wide with the cutting radius of 60 mm, and the angle of incidence of the laser stripe is 5.7° with respect to the surface. Comparison of the curves in Fig 5-29 (a) and (b) shows that after removing the least squares mean line, the misaligned light section is almost the same as the perfectly aligned light section. In fact, there is a small difference between the two curves; however, the difference is only in the order of a fraction of a micrometer, which can be ignored compared to the amplitude of the curves. Another simulation with 10° of
misalignment shows the difference is no more than 1 micrometer. Further simulations with different cutter mark widths show the similar results. Therefore, it is concluded that misalignment of light sections can be acceptably corrected by removing the least squares of the misaligned light section, when the angle of misalignment is not too large. Moreover, according to our empirical observations, misalignment larger than 5° is easy to discern with the eye.

Fig. 5-29 Simulated effects of removal of the least squares of a misaligned light section

5.6 Differential Light Sectioning method

It is mentioned earlier that calibration of the field of view of the imaging system is not difficult, but calibration of the angle of incidence subtended by the projected laser beam and the wood sample surface is very difficult because it is difficult to measure the angle between the base plane of the laser and the wood sample surface. If taking into account the surface defects like warp, the measurement becomes more difficult. In contrast, however, it is relatively easier to measure and calibrate the angle that the laser has rotated on the goniometer. Calibration of the goniometer is discussed in Chapter 3.
A new method, which is based on two laser projections, was therefore proposed for the Light Sectioning method. (See Fig. 5-30) This method is referred to as the Differential Light Sectioning method.

![Fig. 5-30 Schematic of Differential Light Sectioning method](image)

Suppose laser is projected onto the surface at two different angles $\alpha_1$ and $\alpha_2$, making two light sections respectively. If the actual surface height is $h$, and the corresponding height in the light section made by the laser with angle $\alpha_1$ is $h_1$, and the corresponding height in the light section made by the laser with angle $\alpha_2$ is $h_2$.

Although it is not easy to measure $\alpha_1$ and $\alpha_2$ accurately with abovementioned reasons, it is not difficult to measure the difference between $\alpha_1$ and $\alpha_2$, i.e. $\alpha$ in Fig 5-30. The difference in angle can be read and calculated from the goniometer. The light section heights $h_1$ and $h_2$ can be calculated from the images with the algorithm described in the previous section. Therefore, it is assumed that $\alpha$, $h_1$ and $h_2$ are known. There are:

$$\alpha = \alpha_2 - \alpha_1$$

Eq. 5-7

$$\frac{h}{h_1} = \tan(\alpha_1)$$

Eq. 5-8

$$\frac{h}{h_2} = \tan(\alpha_2)$$

Eq. 5-9

From equations Eq. 5-7, Eq. 5-8, and Eq 5-9, Eq. 5-10 is derived.

$$\alpha \tan\left(\frac{h}{h_2}\right) - \alpha \tan\left(\frac{h}{h_1}\right) = \alpha$$

Eq. 5-10
Solving Eq. 5-10 gives:

\[ h = \frac{h_1 - h_2 \pm \sqrt{(h_2 - h_1)^2 - 4\tan^2 \alpha \cdot h_1 \cdot h_2}}{2\tan \alpha} \]

Eq. 5-11

Note that there will be two solutions, but only one of them will be the real solution. It will be easy to establish which one is the real solution by *a priori* knowledge.

According to the above derivation, the actual surface height can be calculated from two light sections taken at the same place provided that the angle between the two light projections is known.

In order to prove this method, two images were taken, which are shown in Fig. 5-31 and Fig. 5-32. The images are calibrated to be 22512 µm over 1280 pixels longitudinally across the images. The light-section-making light strip is projected from the topside of the images. The projection angle for light section 1, i.e. \( \alpha_1 \), is 4.64°; and the projection angle for light section 2, \( \alpha_2 \), is 5.79°. Note that there are some uncertainties with these two angle measurements due to the reason mentioned at the beginning of this section. However, the uncertainties are common to the two angle measurements, therefore the angle difference of \( \alpha_1 \) and \( \alpha_2 \) is certain, i.e. \( \alpha = 1.15° \).

The light sections extracted from Fig. 5-31 and Fig. 5-32 are plotted together in Fig. 5-33, where light section 1 is obtained from Fig. 5-31, and light section 2 from Fig. 5-32. Also, the light section profiles are compared to the laser profile in Fig. 5-34. The Y-axis
in Fig 5-33 is light section height in pixels, while the Y-axis in Fig 5-34 is relative height. The procedure for calculation of the relative height is described in Section 5.4.

**Fig. 5-33 Comparison of two light sections**

**Fig. 5-34 Comparison of the light section profiles to the laser profile**
In Fig. 5-33, peaks and valleys on the profiles are marked with 'x' and '+' respectively. Y-axis distances between these turning points are calculated and they are stored in \( h_1 \) for light section 1 and \( h_2 \) for light section 2. Then \( h \) is calculated from \( h_1 \), \( h_2 \) and \( \alpha \) with Eq. 5-11. Values of \( h_1 \), \( h_2 \) and \( h \) are shown in Table 5-3. Columns 1 and 2 are \( h_1 \) and \( h_2 \) in pixels; column 3 is \( h \) in pixels; and column 4 is \( h \) in micrometers, column 5 is the heights obtained from the laser profile. Note that the laser profile does not have a point corresponding to the last local minimum point on the light section profiles. So the last row of the last column in Table 5-3 is unavailable.

**Table 5-3 Heights calculated with the Differential Light Sectioning method**

<table>
<thead>
<tr>
<th>( h_1 ) (pixel)</th>
<th>( h_2 ) (pixel)</th>
<th>( h ) (pixel)</th>
<th>( h^{*22512/1280} ) (( \mu )m)</th>
<th>( h ) from the laser profile (( \mu )m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>6.38</td>
<td>3.28</td>
<td>0.14</td>
<td>2.38</td>
<td>7.16</td>
</tr>
<tr>
<td>4.95</td>
<td>3.78</td>
<td>0.32</td>
<td>5.70</td>
<td>4.35</td>
</tr>
<tr>
<td>13.83</td>
<td>10.55</td>
<td>0.90</td>
<td>15.82</td>
<td>18.54</td>
</tr>
<tr>
<td>15.76</td>
<td>12.73</td>
<td>1.34</td>
<td>23.59</td>
<td>19.34</td>
</tr>
<tr>
<td>4.65</td>
<td>4.13</td>
<td>0.76</td>
<td>13.44</td>
<td>8.20</td>
</tr>
<tr>
<td>4.09</td>
<td>3.30</td>
<td>0.35</td>
<td>6.14</td>
<td>7.58</td>
</tr>
<tr>
<td>10.46</td>
<td>8.89</td>
<td>1.21</td>
<td>21.26</td>
<td>17.40</td>
</tr>
<tr>
<td>6.24</td>
<td>4.82</td>
<td>0.43</td>
<td>7.51</td>
<td>15.94</td>
</tr>
<tr>
<td>6.98</td>
<td>4.83</td>
<td>0.32</td>
<td>5.56</td>
<td>12.49</td>
</tr>
<tr>
<td>7.99</td>
<td>6.73</td>
<td>0.86</td>
<td>15.17</td>
<td>13.47</td>
</tr>
<tr>
<td>9.09</td>
<td>7.52</td>
<td>0.88</td>
<td>15.54</td>
<td>14.49</td>
</tr>
<tr>
<td>6.15</td>
<td>4.41</td>
<td>0.31</td>
<td>5.54</td>
<td>12.62</td>
</tr>
<tr>
<td>10.46</td>
<td>8.33</td>
<td>0.83</td>
<td>14.59</td>
<td>14.08</td>
</tr>
<tr>
<td>10.07</td>
<td>9.45</td>
<td>3.47</td>
<td>60.95</td>
<td>15.23</td>
</tr>
<tr>
<td>8.94</td>
<td>7.96</td>
<td>1.50</td>
<td>26.33</td>
<td>N/A</td>
</tr>
</tbody>
</table>

After a close study on Table 5-3, it is found that there is an extraordinary value, 60.95 \( \mu \)m, in the second to last row of the fourth column. Mathematically, there is nothing with this value. Physically, however, this value is too large, according to \textit{a priori} knowledge. The only explanation for that will be that surface height measurements from the Light Sectioning method are not reliable, as discussed at the end of Section 5.4. This proposition can be further supported by the fact in Table 5-3 that the heights obtained
with the differential light section method generally do not agree with the heights measured from the laser profile, and at quite a few points the differences are remarkable.

There is another fact that supports the above proposition. According to the model shown in Fig. 5-30, the ratios of h1 to h2 should be a fix number or closely around a fix number. However, the ratios of h1 to h2 shown in Table 5-3 vary in a large range from 1.07 to 1.95. These ratios are listed in Table 5-4.

<table>
<thead>
<tr>
<th>h1 (pixel)</th>
<th>h2 (pixel)</th>
<th>h1/h2</th>
</tr>
</thead>
<tbody>
<tr>
<td>638</td>
<td>328</td>
<td>1.95</td>
</tr>
<tr>
<td>495</td>
<td>378</td>
<td>1.31</td>
</tr>
<tr>
<td>1383</td>
<td>1055</td>
<td>1.31</td>
</tr>
<tr>
<td>1576</td>
<td>1273</td>
<td>1.24</td>
</tr>
<tr>
<td>465</td>
<td>413</td>
<td>1.13</td>
</tr>
<tr>
<td>409</td>
<td>330</td>
<td>1.24</td>
</tr>
<tr>
<td>1046</td>
<td>889</td>
<td>1.18</td>
</tr>
<tr>
<td>624</td>
<td>482</td>
<td>1.30</td>
</tr>
<tr>
<td>698</td>
<td>483</td>
<td>1.45</td>
</tr>
<tr>
<td>799</td>
<td>673</td>
<td>1.19</td>
</tr>
<tr>
<td>909</td>
<td>752</td>
<td>1.21</td>
</tr>
<tr>
<td>615</td>
<td>441</td>
<td>1.39</td>
</tr>
<tr>
<td>1046</td>
<td>833</td>
<td>1.26</td>
</tr>
<tr>
<td>1007</td>
<td>945</td>
<td>1.07</td>
</tr>
<tr>
<td>894</td>
<td>796</td>
<td>1.12</td>
</tr>
</tbody>
</table>

Although the light section heights h1 and h2 do not agree well, the peak-to-peak widths measured from the two light sections are close to each other, and they are both close to the widths measured from the laser profile. The peak-to-peak widths measured from these two light sections, along with the peak-to-peak widths measured from the laser profile, are listed in Table 5-5. The largest difference among the measurement triplets is about less than 10% of the widths.

In conclusion, similar to the conventional Light Sectioning method, the surface height measured with the Differential Light Sectioning method is not reliable either, although the cutter mark peak-to-peak width measurement is acceptable. This conclusion
will inevitably lead to another conclusion that the Differential Light Sectioning method does not have any advantages over the conventional Light Sectioning method, and therefore it is not worth further studies.

Table 5-5 Width comparison

<table>
<thead>
<tr>
<th>Widths measured from light section 1 (mm)</th>
<th>Widths measured from light section 2 (mm)</th>
<th>Widths measured from the laser profile (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.88</td>
<td>1.74</td>
<td>1.84</td>
</tr>
<tr>
<td>2.90</td>
<td>2.97</td>
<td>2.92</td>
</tr>
<tr>
<td>1.99</td>
<td>1.97</td>
<td>2.09</td>
</tr>
<tr>
<td>2.67</td>
<td>2.71</td>
<td>2.67</td>
</tr>
<tr>
<td>2.44</td>
<td>2.41</td>
<td>2.34</td>
</tr>
<tr>
<td>2.13</td>
<td>2.11</td>
<td>2.27</td>
</tr>
<tr>
<td>2.64</td>
<td>2.71</td>
<td>2.54</td>
</tr>
</tbody>
</table>

5.7 Limitations of the Light Sectioning method

Experiment shows that the Light Sectioning method and the Differential Light Sectioning method both have a limitation, that is, widths can be measured relatively well in general, but heights measurements are not satisfactory. For the Light Sectioning method, height measurements are considerably different from those measured from the laser profile. For the Differential Light Sectioning method, heights measured from the two light sections are not in proportion, which actually makes the Differential Light Sectioning method ineffective. This has been proved with many light section experiments.

The reason for the limitation must be related to the relatively coarse nature of wood surfaces. The model in Fig. 5-1 assumes that the surface height does not vary along the Y-axis. Therefore, the model surface is smooth along the Y-axis, with surface height variations only along the X-axis. According to the model, light sections taken parallel to the Y-axis in the model in Fig. 5-1 should be the same. However, this is only an ideal assumption. The real wood surface is very complicated. Fig. 5-35 shows an image of a real wood surface, which has a FOV of 41.5 x 33.2 mm and resolution of 640x512. The illumination for the image is directed from the topside of the image, rather than from the left or right hand side. This arrangement of illumination accents the surface variations along the vertical direction of the image. The cutter marks on the surface are along the
horizontal direction in the image. Although the surface has some defects such as pencil marks and scratches, which are not typical on fresh cut wood surfaces, the topography along the vertical direction in the image is typical on wood surfaces.

Therefore, it is concluded that the light-sectioning model shown in Fig 5-1 can be compromised by the surface height variations along the Y-axis. This is illustrated in Fig. 5-36
Suppose the heights between the peak and the valley are the same, so are the angles of incidence. Because of the bump in Situation B, the light section height in Situation B is shorter than that in Situation A. This is only a very simple example of how a real wood surface affects the form of the light section. The real situation can be much more complicated. This is why heights measured from different light sections are not in proportion, and therefore the Differential Light Sectioning method is not practical. For the conventional Light Sectioning method, the measured surface heights are not as reliable as the measured peak-to-peak surface widths due to the same reasons.

Fig. 5-36 Compromised light section

Situation A in Fig. 5-36 shows an ideal surface, where both the peak and the valley are even in height. Situation B shows a real surface, where there is a bump in the valley.
from each other on the surface. This makes it less realistic to hold all the light sections in one image. However, this problem may be addressed in the future research.

5.8 Conclusions

The Light Section method can be used to measure cutter mark widths, but cutter mark heights cannot be reliably measured with the method. This is due to the fact that surface height variations do not only take place along the feed direction (the first surface height detail), but also take place perpendicularly to the feed direction (the secondary surface height detail). The secondary surface height detail makes the reliability of surface heights measured with the Light Sectioning method compromised. It also renders the Light Sectioning method unsuitable for cutter mark wave widths less than 1.5 mm where the first surface height detail (<5 μm) is more or less at the same order as the secondary surface height detail.

Despite the promise of the Differential Light Sectioning method, the secondary surface height detail makes the method highly unreliable.

The next chapter will explore the Shadow Analysis method, which approaches the problem of surface measurement from another angle.

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6 This is calculated with the typical cutterhead radius of 60mm
6. Shadow Analysis method

Among the investigations on the Shadow Analysis methods done by previous researchers, Hoffmeister's work are the latest and most advanced. Hoffmeister have successfully measured cutter mark widths with this method. However, there are still some issues in this method worthy of further study. These issues are listed below.

- How does the Shadow Analysis method compare to other methods such as stylus tracing and the Light Sectioning method
- Non-collimated and collimated light, which one is better to make shadows
- Whether this method can be used to measure surface heights

6.1 Discussions over the 'adding column by column' algorithm

In Hoffmeister's paper [2], the algorithm used to measure the cutter mark widths is described as 'adding the grey values line by line'. In order to make this algorithm clearer, an image is taken according to the Shadow Analysis method, and shown in Fig 6-1. The FOV of the image is about 50x40 mm. What the 'adding line by line' algorithm exactly does is illustrated in Fig 6-2. Suppose an image has \( m \) rows and \( n \) columns. The image is mathematically expressed as a matrix \( G(i, j) \), with \( 1 \leq i \leq m \) and \( 1 \leq j \leq n \). The cutter mark direction, i.e. the feed direction, indicated by the arrowed line is parallel to the row of the matrix. As seen in Fig 6-2, the algorithm is actually better described as 'adding column by column', i.e.:

\[
c(j) = \frac{\sum G(i, j)}{m}
\]

Eq. 6-1

the matrix \( G(i, j) \) is converted to a vector \( c(j) \). As a result, a column-wise intensity profile is obtained, and the intensity profile is used by Hoffmeister et al as the basis for the measurement of the cutter mark widths.
In order to further analyse Hoffmeister's research, their experiments are reproduced here. The image in Fig. 6-1 is obtained with metal halide light via a fibre light guide\textsuperscript{7} from the right hand side of the image. Although the angle of incidence needs to be small enough to show the shadows, the angle per se is unnecessary to be known according to the principle of the Shadow Analysis method. Therefore no angle of incidence was measured for the image in Fig. 6-1. As shown in Fig. 6-3, the intensity profile indicates a clear periodicity, which is associated with the periodic variations of the surface height. Although the intensity profile is noisy, the noise is fairly weak compared to the wavy profile. So a low pass filter could easily remove the noise. Here a Savitsky-Golay filter is used and the resultant profile is plotted in Fig. 6-4. A Gaussian filter and a zero-phrase averaging filter were also tried and they largely give the same result.

\textsuperscript{7}The light guide has a condensing lens fixed on the emitting end, which makes the light condensed to some extent, but not collimated.
Cutter mark direction

\[
\begin{array}{cccc}
G(1,1) & G(1,2) & G(1,3) & G(1,n) \\
G(2,1) & G(2,2) & G(2,3) & G(2,n) \\
G(3,1) & G(3,2) & G(3,3) & G(3,n) \\
\vdots & \vdots & \vdots & \vdots \\
G(m,1) & G(m,2) & G(m,3) & G(m,n) \\
\end{array}
\]

\[c(j) = \sum_{i=1}^{j} G(i,j) / m\]

\[
\begin{array}{cccc}
c(1) & c(2) & c(3) & c(n) \\
\end{array}
\]

Fig. 6-2 Adding column by column

![Graph showing intensity profile](image)

Fig. 6-3 Intensity profile
On the intensity profile in Fig. 6-4, the peaks are located with the same algorithm as used in Chapter 5, and marked out on the profile. Hoffmeister believes that the peak to peak distances on the intensity profile are the widths of cutter marks, although in [2, 7], no reasons for that are given. This assumption is reasonable, as the periodic intensity profile is due to the periodic cutter marks on the surface. Although a peak on the intensity profile does not necessarily coincide with a peak on the cutter mark profile, every peak on the intensity profile may very well coincide with roughly the same position in the respective cutter mark waveform. As a result, the distances between the neighbouring peaks equal the widths of cutter marks. This analysis is very intuitive. In Chapter 7, more theoretical analysis will be given.

Illumination on the surface in Fig. 6-1 is not even. This can be seen in the intensity profile in Fig. 6-3 and Fig. 6-4. Light comes from the right hand side of the image, so the summation of intensity values are higher on the right hand side of the intensity profile than on the left hand side in general. However, this is not a problem for the Shadow Analysis method, as the Y-axis values of the peaks on the intensity profile do not matter, and only X-axis values are useful in the measurement of cutter mark widths.
A diffusing screen was used in [2], which is supposed to even the illumination. (See Fig 2-12) However, due to the fact that the light comes in from the side of the field of view, shading illumination is inevitable. In [2], no effort is mentioned to eliminate the effects of uneven illumination.

Since the Shadow Analysis method relies on the periodic variations of intensities, there is a problem: each pixel's intensity value is not solely determined by the cutter marks under oblique illumination. It can be seen in Fig. 6-1 that those areas marked with white ovals are odd in intensity compared to their surrounding areas. Some of the odd bits are dents or scratches made on the surface accidentally, such as mark 1 and 2. Others are high points on the surface such as mark 3 and 4, which reflect light straight into the camera. In addition, inherent natural characteristics of wood, such as annual rings shown in Fig. 6-1 as horizontal dark stripes, could also affect the intensities locally.

With regard to the above problem, Hoffmeister argues that 'because characteristics like annual ring, cracks, resin inclusions are distributed arbitrarily, they do not influence the surface profile due to the summing of many pixel columns. Only the cuts have a preferred direction and are therefore assessed in the light-dark profile [2].' This argument is reasonable. Although Hoffmeister did not explicitly direct their argument to surface defects like scratches and dents, undoubtedly, this argument is also applicable to them.

In order to visualise the result of the Shadow Analysis method, the peaks in Fig. 6-4 are inserted into the original image as white vertical lines, and the resultant image is shown in Fig. 6-5. By comparing Fig. 6-1 and Fig. 6-5, however, it can be found that where the cutter mark ridges are perceived by the human eye perception is not consistent with where the white lines are in Fig. 6-5.
The inconsistency is related to how the human eye perceives cutter marks, or more generally, surface height variations. The human eye, in nature, is more sensitive to intensity contrast than to intensities themselves. The reason why people feel there is a ridge along somewhere on a surface is because there is strong contrast between two sides of the ridge. This situation is illustrated in Fig. 6-6. Suppose B stands for a ridge on the surface, and light rays come in from the right hand side in parallel. Then, the area between A and B on the left hand side of the ridge is dark, and the area between B and C on the right hand side is bright. There is a sharp intensity change at B, which is interpreted as a ridge by the human eye and the brain.

Inspired by the illustration in Fig. 6-6, a new idea is proposed: the ridge on the surface may coincide with the greatest local intensity variation. The intensity varying rate is actually the first derivative of the intensity profile. For the image in Fig. 6-1, the
intensity varying rate, referred to as the first derivative profile, is derived from the intensity profile in Fig. 6-4, and plotted in Fig. 6-7. The local maxima are also marked out on the profile, which are assumed to coincide with the ridges on the surface. Actually the assumption depends on what direction the light is from relative to the image. The origin of the image is normally at the upper left corner, and therefore the X-axis origins of the intensity profile and the first derivative are normally at the left hand side. If the light is from the right hand side of the image, as shown in Fig. 6-1 and Fig. 6-6, then the peaks on the first derivative profile are associated with the ridges on the surface. If the light comes from the left hand side, then the valleys, i.e. the local minima on the first derivative profile should be associated with the ridges.

According to the peaks on the first derivative profile in Fig. 6-7, the cutter mark widths are calculated. Also in order to visualise the ridges established by the new algorithm, imaginary vertical lines are inserted into the original image in Fig. 6-1, and this operation gives Fig. 6-8.

Fig. 6-7 First derivative of the intensity profile shown in Fig. 6-4
Fig. 6-8 Shadow image superimposed with white lines located by the first derivative profile

Compared to Fig. 6-5, Fig. 6-8 appears more consistent with the perception of Fig. 6-1 by the eye. However, that is only a subjective comparison. An objective comparison is given in Table 6-1. The first two columns in the table are the widths in pixels and in mm measured from the intensity profile in Fig. 6-4, and the third and fourth column are the widths in pixels and mm from the first derivative profile in Fig. 6-7, and the last column is the differences between the two sets of measurements. Calibration of the image in Fig. 6-1 gives 51.5 mm over 1280 pixels, or 0.04 mm/pixel.

From Table 6-1, it can be seen that there are only minor differences between the widths measured from the intensity profile in Fig. 6-4 and from the first derivative profile in Fig. 6-7, with a maximum difference of 0.16 mm.

More experiments show the similar result. The widths measured from the first derivative profile are approximately the same as the widths from the intensity profile, although the locations of ridges on the surface can be better identified by the first derivative profile than the intensity profile. Therefore, it is concluded that the first derivative profile cannot improve the measurement of cutter mark widths remarkably.
### Table 6-1 Width comparison

<table>
<thead>
<tr>
<th>Cutter mark widths measured from intensity profile (pixels)</th>
<th>Cutter mark widths measured from intensity profile (mm)</th>
<th>Cutter mark widths measured from first derivative profile (pixels)</th>
<th>Cutter mark widths measured from first derivative profile (mm)</th>
<th>Differences (pixels/mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>50</td>
<td>2.01</td>
<td>50</td>
<td>2.01</td>
<td>0/0</td>
</tr>
<tr>
<td>72</td>
<td>2.90</td>
<td>72</td>
<td>2.90</td>
<td>0/0</td>
</tr>
<tr>
<td>48</td>
<td>1.93</td>
<td>49</td>
<td>1.97</td>
<td>-1/-0.04</td>
</tr>
<tr>
<td>75</td>
<td>3.02</td>
<td>71</td>
<td>2.86</td>
<td>4/0.16</td>
</tr>
<tr>
<td>44</td>
<td>1.77</td>
<td>48</td>
<td>1.93</td>
<td>-4/-0.16</td>
</tr>
<tr>
<td>75</td>
<td>3.02</td>
<td>75</td>
<td>3.02</td>
<td>0/0</td>
</tr>
<tr>
<td>49</td>
<td>1.97</td>
<td>50</td>
<td>2.01</td>
<td>-1/-0.04</td>
</tr>
<tr>
<td>68</td>
<td>2.74</td>
<td>67</td>
<td>2.70</td>
<td>1/0.04</td>
</tr>
<tr>
<td>58</td>
<td>2.33</td>
<td>59</td>
<td>2.37</td>
<td>-1/-0.04</td>
</tr>
<tr>
<td>59</td>
<td>2.37</td>
<td>58</td>
<td>2.33</td>
<td>1/0.04</td>
</tr>
<tr>
<td>68</td>
<td>2.74</td>
<td>67</td>
<td>2.70</td>
<td>1/0.04</td>
</tr>
<tr>
<td>48</td>
<td>1.93</td>
<td>49</td>
<td>1.97</td>
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</tr>
<tr>
<td>76</td>
<td>3.06</td>
<td>76</td>
<td>3.06</td>
<td>0/0</td>
</tr>
<tr>
<td>42</td>
<td>1.69</td>
<td>42</td>
<td>1.69</td>
<td>0/0</td>
</tr>
<tr>
<td>79</td>
<td>3.18</td>
<td>79</td>
<td>3.18</td>
<td>0/0</td>
</tr>
<tr>
<td>41</td>
<td>1.65</td>
<td>40</td>
<td>1.61</td>
<td>1/0.04</td>
</tr>
<tr>
<td>82</td>
<td>3.30</td>
<td>80</td>
<td>3.22</td>
<td>2/0.08</td>
</tr>
<tr>
<td>41</td>
<td>1.65</td>
<td>44</td>
<td>1.77</td>
<td>-3/-0.12</td>
</tr>
<tr>
<td>79</td>
<td>3.18</td>
<td>77</td>
<td>3.10</td>
<td>2/0.08</td>
</tr>
<tr>
<td>46</td>
<td>1.85</td>
<td>48</td>
<td>1.93</td>
<td>-2/-0.08</td>
</tr>
</tbody>
</table>

### 6.2 Comparison to other methods

The same wood sample as used in Chapter 5 (Fig. 5-7) is used again to compare the Shadow Analysis method with the laser profilometer and the Light Sectioning method. The shadow image is shown in Fig. 6-9. The wood sample is only 12 mm or so in width, so the image only shows the useful portion of the original image. The length of the image is 40.16 mm over 1280 pixels. The light source for the image is collimated laser. In contrast, the light source for the image in Fig. 6-1 is non-collimated, from a metal halide light source via a fibre light guide. Issues as to collimated and non-collimated light sources will be discussed in the next section.

Also, it is noticeable that the image in Fig. 6-9 is not in sharp focus. However, since the Shadow Analysis method is essentially an averaging algorithm, so a slightly
defocused image would not make much difference. Actually, this is an advantage of the Shadow Analysis method.

Fig. 6-9 Shadow image

The comparison is shown in Table 6-2, where the first column is the widths measured from the light sectioning profile, and the second column is the widths measured from the laser profile, and the third column is the widths measured from the intensity profile, and the last column is the widths measured from the first derivative profile. The first two columns are actually copied from Table 5-1. The last two columns are measurements using the algorithms described in the last section.

Table 6-2 Comparison between the Shadow Analysis, the laser profilometer and the Light Sectioning method

<table>
<thead>
<tr>
<th></th>
<th>w1: widths from the light section profile (mm)</th>
<th>w2: widths from the laser profile (mm)</th>
<th>w3: widths from the intensity profile (mm)</th>
<th>w4: widths from the first derivative profile (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.11</td>
<td>3.25</td>
<td>3.14</td>
<td>3.01</td>
<td></td>
</tr>
<tr>
<td>2.70</td>
<td>2.52</td>
<td>2.82</td>
<td>2.70</td>
<td></td>
</tr>
<tr>
<td>2.95</td>
<td>2.88</td>
<td>3.01</td>
<td>2.98</td>
<td></td>
</tr>
<tr>
<td>4.10</td>
<td>3.67</td>
<td>3.36</td>
<td>3.51</td>
<td></td>
</tr>
<tr>
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<td>2.95</td>
<td>2.89</td>
<td></td>
</tr>
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<td>2.64</td>
<td>2.83</td>
<td>2.85</td>
<td>2.82</td>
<td></td>
</tr>
<tr>
<td>3.05</td>
<td>2.89</td>
<td>2.92</td>
<td>2.98</td>
<td></td>
</tr>
<tr>
<td>3.30</td>
<td>3.44</td>
<td>3.23</td>
<td>3.29</td>
<td></td>
</tr>
<tr>
<td>3.34</td>
<td>3.04</td>
<td>3.14</td>
<td>3.11</td>
<td></td>
</tr>
<tr>
<td>2.48</td>
<td>2.61</td>
<td>2.76</td>
<td>2.64</td>
<td></td>
</tr>
<tr>
<td>2.99</td>
<td>3.16</td>
<td>2.89</td>
<td>3.01</td>
<td></td>
</tr>
</tbody>
</table>

From Table 6-2, it can be seen that widths measured with the four methods are largely in agreement. The measurement differences between the methods are listed in Table 6-3, and the mean values and standard deviations of these differences are listed in
Table 6-4. The symbols w1, w2, w3, and w4 are defined in Table 6-2. From Table 6-3 and Table 6-4, it can be seen that widths from the two Shadow Analysis methods (w3 and w4) are very close to each other; widths from the Shadow Analysis methods are also fairly close to those from the laser profile, with w2-w4 comparison slightly better than w2-w3 comparison; widths from the shadow analysis methods and those from the Light Sectioning method have relatively large difference, also with w1-w4 comparison slightly better than w1-w3 comparison. Measurements from the Light Sectioning method and the laser profilometer method also have relatively large difference.

Table 6-3 Differences among measurements from the methods

<table>
<thead>
<tr>
<th>w1-w2 (mm)</th>
<th>w1-w3 (mm)</th>
<th>w1-w4 (mm)</th>
<th>w2-w3 (mm)</th>
<th>w2-w4 (mm)</th>
<th>w3-w4 (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>-0.14</td>
<td>-0.03</td>
<td>0.10</td>
<td>0.11</td>
<td>0.24</td>
<td>0.13</td>
</tr>
<tr>
<td>0.18</td>
<td>-0.12</td>
<td>0</td>
<td>-0.30</td>
<td>-0.18</td>
<td>0.12</td>
</tr>
<tr>
<td>0.07</td>
<td>-0.06</td>
<td>-0.03</td>
<td>-0.13</td>
<td>-0.10</td>
<td>0.03</td>
</tr>
<tr>
<td>0.43</td>
<td>0.74</td>
<td>0.59</td>
<td>0.31</td>
<td>0.16</td>
<td>-0.15</td>
</tr>
<tr>
<td>-0.35</td>
<td>-0.31</td>
<td>-0.25</td>
<td>0.04</td>
<td>0.10</td>
<td>0.06</td>
</tr>
<tr>
<td>-0.19</td>
<td>-0.21</td>
<td>-0.18</td>
<td>-0.02</td>
<td>0.01</td>
<td>0.03</td>
</tr>
<tr>
<td>0.16</td>
<td>0.13</td>
<td>0.07</td>
<td>-0.03</td>
<td>-0.09</td>
<td>-0.06</td>
</tr>
<tr>
<td>-0.14</td>
<td>0.07</td>
<td>0.01</td>
<td>0.21</td>
<td>0.15</td>
<td>-0.06</td>
</tr>
<tr>
<td>0.30</td>
<td>0.20</td>
<td>0.23</td>
<td>-0.10</td>
<td>-0.07</td>
<td>0.03</td>
</tr>
<tr>
<td>-0.13</td>
<td>-0.28</td>
<td>-0.16</td>
<td>-0.15</td>
<td>-0.03</td>
<td>0.12</td>
</tr>
<tr>
<td>-0.17</td>
<td>0.10</td>
<td>-0.02</td>
<td>0.27</td>
<td>0.15</td>
<td>-0.1</td>
</tr>
</tbody>
</table>

Table 6-4 Means and standard deviations of differences

<table>
<thead>
<tr>
<th>w1-w2</th>
<th>w1-w3</th>
<th>w1-w4</th>
<th>w2-w3</th>
<th>w2-w4</th>
<th>w3-w4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean (mm)</td>
<td>0.21</td>
<td>0.20</td>
<td>0.15</td>
<td>0.15</td>
<td>0.12</td>
</tr>
<tr>
<td>Std (mm)</td>
<td>0.11</td>
<td>0.20</td>
<td>0.17</td>
<td>0.11</td>
<td>0.07</td>
</tr>
</tbody>
</table>

6.3 Collimated light or non-collimated light

For the Shadow Analysis method, there is a choice for the light source: collimated or non-collimated.

In Zhao’s research [39, 103, 104] and Faust’s research [38], laser illumination was employed. Laser light is easy to be made collimated theoretically. Hoffmeister utilised non-collimated light in [2, 7]. In Hoffmeister’s test rig shown in Fig 2-12, a diffusing
screen was used behind a double condenser to make the illumination even, which also made the light non-collimated effectively.

In order to compare collimated light and non-collimated light, two images were taken from the same wood sample, but with non-collimated illumination and collimated illumination respectively. Fig. 6-10 shows the image with non-collimated illumination (metal halide light via a fibre light guide\(^8\)), while Fig. 6-11 shows the image with collimated illumination (collimated laser light). The FOV of these two image is about 42×33.6 mm.

Fig. 6-10 Shadow image with non-collimated illumination

---

\(^8\) No condensing lens was fixed on the light guide. Therefore the light emitted from the light guide is more diffuse than that used for the image in Fig. 6-1. This is meant to strengthen the contrast between Fig. 6-10 with non-collimated light and Fig. 6-11 with collimated light.
Table 6-5 shows the comparison between the widths measured from the intensity profiles of Fig. 6-10 and Fig. 6-11. The first two columns are the widths in millimetres; the third column is the differences between the first two columns; the last column is the widths measured with the laser profilometer. First of all, the widths measured from Fig. 6-10 and Fig. 6-11, and widths measured with the laser profilometer are largely close to each other. Some differences between the widths measured from Fig. 6-10 and Fig. 6-11 are a little large, such as 0.33 mm, 0.29 mm, and 0.23 mm. For these measurements, widths from Fig. 6-10 are closer to widths from the laser profilometer than widths from Fig. 6-11.

Table 6-6 shows the comparison between the widths measured from the first derivative profiles of Fig. 6-10 and Fig. 6-11. The first two columns are the widths in millimetres; the second column is the differences between the first two columns; the last column is the widths measured with the laser profilometer. As seen in the table, widths measured with all methods are close to each other.
Table 6-5 Comparison of widths measured with the intensity profiles from Fig. 6-10 and Fig. 6-11

<table>
<thead>
<tr>
<th>Widths measured from the intensity profile of the image in Fig 6-10 (mm)</th>
<th>Widths measured from the intensity profile of the image in Fig 6-11 (mm)</th>
<th>Differences between widths in Fig 6-10 and Fig 6-11 (mm)</th>
<th>Widths measured from the laser profile (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.45</td>
<td>2.45</td>
<td>0</td>
<td>2.45</td>
</tr>
<tr>
<td>1.96</td>
<td>1.93</td>
<td>0.03</td>
<td>2.05</td>
</tr>
<tr>
<td>3.17</td>
<td>3.20</td>
<td>-0.03</td>
<td>3.15</td>
</tr>
<tr>
<td>1.53</td>
<td>1.47</td>
<td>0.07</td>
<td>1.45</td>
</tr>
<tr>
<td>3.33</td>
<td>3.46</td>
<td>-0.13</td>
<td>3.50</td>
</tr>
<tr>
<td>1.50</td>
<td>1.47</td>
<td>0.03</td>
<td>1.40</td>
</tr>
<tr>
<td>3.26</td>
<td>3.04</td>
<td>0.23</td>
<td>3.45</td>
</tr>
<tr>
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<td>1.45</td>
</tr>
<tr>
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<td>3.40</td>
</tr>
<tr>
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<td>1.93</td>
<td>-0.23</td>
<td>1.70</td>
</tr>
<tr>
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<td>2.84</td>
<td>-0.03</td>
<td>2.80</td>
</tr>
<tr>
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<td>2.32</td>
<td>-0.03</td>
<td>2.35</td>
</tr>
<tr>
<td>2.42</td>
<td>2.42</td>
<td>0</td>
<td>2.40</td>
</tr>
<tr>
<td>2.42</td>
<td>2.48</td>
<td>-0.07</td>
<td>2.45</td>
</tr>
<tr>
<td>2.32</td>
<td>2.25</td>
<td>0.07</td>
<td>2.25</td>
</tr>
<tr>
<td>2.81</td>
<td>2.74</td>
<td>0.07</td>
<td>2.75</td>
</tr>
</tbody>
</table>

Table 6-6 Comparison of widths measured with the first derivative profiles from Fig. 6-10 and Fig. 6-11

<table>
<thead>
<tr>
<th>Widths measured from the first derivative profile of the image in Fig 6-10 (mm)</th>
<th>Widths measured from the first derivative profile of the image in Fig 6-11 (mm)</th>
<th>Differences between widths in Fig 6-10 and Fig 6-11 (mm)</th>
<th>Widths measured from the laser profile (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.42</td>
<td>2.45</td>
<td>-0.03</td>
<td>2.45</td>
</tr>
<tr>
<td>1.99</td>
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<td>2.45</td>
</tr>
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<td>2.15</td>
<td>2.19</td>
<td>-0.03</td>
<td>2.25</td>
</tr>
<tr>
<td>2.84</td>
<td>2.81</td>
<td>0.03</td>
<td>2.75</td>
</tr>
</tbody>
</table>
Accordingly, it is concluded that collimated illumination and non-collimated illumination make no difference to the Shadow Analysis method in terms of measuring cutter mark widths.

However, there is an issue that needs considering when collimated illumination is used. As illustrated in Fig. 6-12, when the angle of incidence is smaller than a certain angle, then some low ridges on the surface may be eclipsed in the shadows made by adjacent high ridges. In the image taken in the circumstances, information on low ridges will be lost. In contrast, non-collimated illumination will not normally have this problem because light rays go in various directions.

![This peak is eclipsed in the shadow](image)

Fig. 6-12 A problem with the Shadow Analysis method using collimated illumination

### 6.4 Multi-angle Shadow Analysis method

So far, the Shadow Analysis method has been tested and proven to be able to measure cutter mark widths. This section describes investigations in obtaining cutter mark heights from shadows. First, four geometric models of the Shadow Analysis method are introduced. Then, experiments are described, which is followed by analysis and conclusions.

#### 6.4.1 Geometric Model 1

Fig. 6-13 is a simplified model for the wood surface. The model assumes that the cutter locus is a circular arc with a radius of \( R \), and the cutter mark has the same high peaks on both sides. As mentioned before, the real shape of a cutter mark is not a circular arc but a trochoid. However, the approximation error is proved in [5] very small, \(< 5\%\) for typical rotary machining processes used in the woodworking industry, so the surface is often approximated by a series of circular arcs for simplicity.

Suppose collimated light is used and the light comes in at an angle of \( \alpha \) relative to the imaginary line that links the two peaks of the cutter mark, projecting a shadow of \( L_1 \) in width. In addition, the width of the cutter mark is \( L_4 \), and the height is \( h \). According to
the geometry in Fig. 6-13, equations Eq. 6-2 and Eq. 6-3 are established. Among the elements in the equations, L1 and L4 can be obtained from the image, and $\alpha$ can be measured from the goniometer, which has been described in Chapter 3 (Testing). Therefore, there are only two elements in the equations unknown, $h$ and $R$. In theory, the equations are solvable.

However, there are two problems with the model. Firstly, the peaks of a real cutter mark are very likely to be at different heights. The assumption of the peaks being at the same height will inevitably introduce errors. More important, the assumption will give a misrepresentation of the real surface. Consider the situations in Fig. 6-14. On a real wood surface, peaks are at different heights, as shown in upper part of the figure. If calculating the surface according to the model in Fig. 6-13, then the peaks on the surface will be at the same level, as shown in lower part of Fig. 6-14. Clearly, this result will be misleading.
6.4.2 Geometric Model 2

Geometric model 2 for the Shadow Analysis method is shown in Fig. 6-15. This model is the same as geometric model 1 in all respects, except that the two peaks on the cutter mark waveform have different heights. The difference is $\Delta h$. $L_4$ is the width of the imaginary cutter mark, which has the same height at both sides. Likewise, suppose $L_1$ and $L_3$ can be measured from the image, and the angle $\alpha$ can be calculated from the goniometer. Then there are three equations among the elements:

$$h = R - \sqrt{R^2 - \left(\frac{L_4}{2}\right)^2}$$

Eq. 6-4

$$a \tan \left( \frac{\sqrt{R^2 - \left(\frac{L_1 - L_4}{2}\right)^2} - (R - h)}{L_1} \right) = \alpha$$

Eq. 6-5

$$\sqrt{R^2 - (R-h)^2} - \sqrt{R^2 - (R-h+\Delta h)^2} = L_4 - L_3$$

Eq. 6-6
Among the three equations, $L_1$, $L_3$, and $\alpha$ are known, and $\Delta h$, $R$, $h$, and $L_4$ are unknown. In theory, the equations are unsolvable as there are more unknown elements than the number of equations.

### 6.4.3 Geometric Model 3

The problem with geometric model 2 is that there are more unknown elements than the relationships that can be found among them. Particularly, $\Delta h$ is the key problem that makes the equations unsolvable. In order to deal with this problem, a new model is constructed, as shown in Fig. 6-16. In the new model, there are two light sources located at both sides of the surface. These two light sources work at different times, therefore two shadow images are made. All the symbols in the model have the same denotation as defined in the previous models. Among the elements, $L_1$, $L_2$, and $L_3$ are known from the images, and $\alpha_1$ and $\alpha_2$ from the goniometer, while elements that remain unknown are $R$, $h$, $L_4$ and $\Delta h$. Similarly, there are 4 relationships among the elements in the model, which are expressed in the following equations.
Since there are four independent equations for the four unknowns, the equations are solvable in theory. However, it is impossible to find out the analytical solutions due to the complexity of the equations. Only approximations can be obtained with a certain error tolerance. The approximation algorithm will be discussed in the next section.
6.4.4 Geometric Model 4

Geometric model 3 appears fine in theory. However, there is a practical problem that \( \alpha_1 \) and \( \alpha_2 \) are not easy to measure accurately. The same problem has occurred in the Light Sectioning method (Chapter 5), where a differential method was used to deal with the problem. Accordingly, another model is constructed to deal with the problem with the approach used in the differential Light Sectioning method. The model is illustrated in Fig. 6-17.

![Geometric Model 4 Diagram](image)

This model is the same as geometric model 3, except that there are two light projections from each side of the surface, with angles \( \alpha_1 \) and \( \alpha_2 \) respectively. Also two images are produced. Among the elements in Fig. 6-17, \( L_{r1} \), \( L_{r2} \), \( L_{l1} \), \( L_{l2} \), and \( L_3 \) can be obtained from the images, \( \alpha_1 \) and \( \alpha_2 \) can be obtained from the goniometer. \( R \), \( L_4 \), \( h \), and \( \Delta h \) are still unknown. Similar to model 3, there are 4 equations.

\[
h = R - \sqrt{R^2 - \left( \frac{L_4}{2} \right)^2}
\]

Eq. 6-11
Similarly, the equations can be solved in theory, but only some approximation solutions can be obtained. The following is the algorithm that was used to get the approximate solutions:

1. Set up an error tolerance $\epsilon$

2. Construct four functions from Eq. 6-11 to Eq. 6-14 by moving all the elements in the equations to one side of the equal marks:

\[
F_1(R, h, L_4, \Delta h) = h + \sqrt{R^2 - \left(\frac{L_4}{2}\right)^2} - R
\]

\[
F_2(R, h, L_4, \Delta h) = \tan^{-1}\left(\frac{R^2 - \left(\frac{L_1 - L_4}{2}\right)^2 - (R - h)}{L_1}\right) - \tan^{-1}\left(\frac{R^2 - \left(\frac{L_2 - L_4}{2}\right)^2 - (R - h)}{L_2}\right) - \alpha_1
\]

\[
F_3(R, h, L_4, \Delta h) = \sqrt{R^2 - (R - h)^2} - \sqrt{R^2 - (R - h + \Delta h)^2} - L_4 + L_3
\]
\[
F_4(R, h, L4, \Delta h) = \\
a \tan \left( \sqrt{\frac{R^2 - \left( Ll1 - \frac{L4}{2} \right)^2}{Ll1}} - (R - h) \right) - a \tan \left( \sqrt{\frac{R^2 - \left( Ll2 - \frac{L4}{2} \right)^2}{Ll2}} - (R - h) \right) - \alpha 2
\]

Eq. 6-18

Then, construct a function \( F \) from the above functions:

\[
F(R, h, L4, \Delta h) = \\
F_1^2(R, h, L4, \Delta h) + F_2^2(R, h, L4, \Delta h) + F_3^2(R, h, L4, \Delta h) + F_4^2(R, h, L4, \Delta h)
\]

Eq. 6-19

3 Construct four vectors as below.

- \( R = [r_i] \), where \( r_i = r_i + (i - 1) \cdot r_i \), \( 1 \leq i \leq m \)
- \( h = [h_j] \), where \( h_j = h_1 + (j - 1) \cdot h_j \), \( 1 \leq j \leq n \)
- \( L4 = [L4_p] \), where \( L4_p = L4_1 + (p - 1) \cdot L4_1 \), \( 1 \leq p \leq u \)
- \( \Delta h = [\Delta h_q] \), where \( \Delta h_q = \Delta h_1 + (q - 1) \cdot \Delta h_1 \), \( 1 \leq q \leq v \)

Note that \( r_i, h_j, L4_p, \Delta h_q \) and \( r_i, h_j, L4_p, \Delta h_q \) have to be estimated first. However, the estimations can be done reasonably with the help of prior knowledge.

4. Construct a 4-dimensional matrix \( M \), with the length of each dimension being the length of vector \( R, h, L4, \Delta h \) respectively

\[
M = [m_{iopq}], \text{ where } 1 \leq i \leq m, 1 \leq j \leq n, 1 \leq p \leq u, \text{ and } 1 \leq q \leq v.
\]

5 Run the following algorithm

For \( i = 1 \) To \( m \)

For \( j = 1 \) To \( n \)

For \( p = 1 \) To \( u \)

For \( q = 1 \) To \( v \)

\[
m_{iopq} = F(r_i, h_j, L4_p, \Delta h_q)
\]

End

End

End

6 Find out the indices, \( i_o, j_o, p_o, q_o \), of the element in \( M \), where
• $m_{t_1j_1p_1q_1} = \min(m_{ypq})$

• If $m_{t_1j_1p_1q_1} \leq \varepsilon$, then $(r_z, h_{j_z}, l_4, p_z, \Delta h_{q_z})$ are the solutions;

• If NOT, then repeat steps 3 to 6. In step 3, the vectors are constructed around $(r_z, h_{j_z}, l_4, p_z, \Delta h_{q_z})$, with smaller steps $r_x, h_x, l_4, \Delta h_z$.

The efficiency of the algorithm is determined by the numbers of elements in the vectors $R$, $h$, $L4$, and $\Delta h$. Appropriately selected ranges and steps for the vectors can speed up the algorithm. A practical strategy is to choose a large range and a large step first for each vector, then focus the range around the previous result with finer steps.

The algorithm might not be an optimal one in terms of computation efficiency. However, considering the computational capacity of modern computers, the algorithm is feasible. If necessary, the algorithm may be optimised in the future studies.

### 6.4.5 Experiments with Multi-Angle Shadow Analysis method

In order to implement the Multi-Angle Shadow Analysis method, collimated illumination is necessary, according to the geometric models. In addition, $L_{11}$, $L_{12}$, $L_{r1}$, $L_{r2}$, and $L_3$ in Fig. 6-17 must be measured from the images. Measuring $L_3$ has been dealt with in the conventional Shadow Analysis method. Measuring $L_{11}$, $L_{12}$, $L_{r1}$, and $L_{r2}$ is actually measuring the width of the shadow in a cutter mark waveform.

As illustrated in Fig. 6-18, when light comes from the right hand side, $L_{r1}$ and $L_{r2}$ are the length of $BC$, while when light comes from the left hand side, $L_{11}$ and $L_{12}$ are the length of $AB$. The key for both of the situations is to locate $B$. To locate $A$ and $C$ is just to locate the ridges on a surface, for which the first derivative profile described in Section 6.1 can be used. Similarly, the same first derivative profile can also be used to locate $B$.

When light comes from the right hand side, as the situation shown in Fig. 6-18 (A), the local maxima on the first derivative profile correspond to locations of $A$ and $C$, while the local minima correspond to the location of $B$. When light comes from the left hand side, as the situation shown in Fig. 6-18 (B), the local minima on the first derivative profile correspond to the locations of $A$ and $C$, while the local maxima correspond to the location of $B$. 

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There is a concern as to the angle between the light path 1 and the light path 2, which cannot be too large. The reason is illustrated in Fig. 6-19, which shows an example for the maximum angle between the light path 1 and the light path 2. Suppose the width $W$ is 2.5 mm, and the cutting radius is 60 mm. The minimum angle of incidence for the light path 2 is 0°, suppose no problem shown in Fig. 6-12 exists. The maximum angle of incidence for the light path 1 is coincident with the tangent at the peak point, which is $\tan(W/2/R) = 1.2°$. Therefore the angle $\theta$ between the light path 1 and the light path 2 is at the most 1.2° for the case.

Bearing in mind above concerns, four images were taken from a wood sample with nominally 3 mm cutter mark widths and ±5 μm spindle vibration. These images are shown in Fig. 6-20 to Fig. 6-23 respectively. The light source for these images is a diode laser through a beam expander. The laser and the beam expander are described in Chapter 3.

For Fig. 6-20 and Fig 6-21, the light comes from the left hand side of the images. Fig 6-20 is for measuring L11, Fig. 6-21 is for measuring L12. For Fig. 6-22 and Fig 6-23, the light comes from the right hand side of the images. Fig 6-22 is for measuring Lr1,
and Fig. 6-23 is for measuring Lr2. L3 can be measured from all of the images, and estimated as the average of the measurements.
Accordingly, L11, L12, Lr1, Lr2, and L3 are measured from the images with the method described in Fig. 6-18 and the corresponding texts. The measurements are listed in Table 6-7, Table 6-8, and Table 6-9. The angles of incidence for the images in Fig. 6-20 and Fig. 6-21 are made approximately 0.32° and 1.18°, and therefore the angle difference, i.e. α2, is 0.86°, which is accurate. The angles of incidence for the images in Fig. 6-22 and Fig. 6-23 are made equal to the angles for images in Fig. 6-20 and Fig. 6-21, and therefore α1 equals α2.

**Table 6-7 L3 measurements**

<table>
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<tr>
<th>L3-1 (pixel)</th>
<th>L3-2 (pixel)</th>
<th>L3-3 (pixel)</th>
<th>L3-4 (pixel)</th>
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<tbody>
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**Table 6-8 L11 and L12 measurements**

<table>
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<th>L12-L11</th>
</tr>
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<td>67</td>
<td>4</td>
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Table 6-9 Lr1 and Lr2 measurements

<table>
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</table>

Finally, the algorithm explained in the last section is implemented in MATLAB to compute the surface profile and it takes about 15 minutes to run on a P4 2.8G PC. As a result, a multi-angle shadow analysis (MASA) profile is obtained. This MASA profile is plotted in Fig. 6-24, along with a laser profile measured with the laser profilometer, and a simulated surface profile. The simulated surface profile is computed with the following conditions and assumptions:

- The pitch of the cutter mark waveforms is 3 mm
- The spindle vibration amplitude is ±5 μm
- The cutter mark waveforms are approximated to be circular arcs

The first two items of the above are based on the fact that the sample was cut with a nominal 3 mm cutter mark pitch and ±5 μm spindle vibration. More information about cutting wood samples with a certain cutter mark pattern is referred to Chapter 3 Section 3.7.
Fig. 6-24 MASA profile vs laser profile

By comparison of the profiles in Fig. 6-24, it can be seen that the MASA profile is similar to the laser profile in widths of cutter marks, but there are some differences in heights, especially those circled valleys on the laser profile are not deep enough. Note that due to the fact that the MASA profile is actually another simulated profile, there are sharp peaks on the profile. In contrast, because the laser profile has been low pass filtered, there are only rounded peaks on the profile.

It can also be seen in Fig. 6-24 that the MASA profile is closer to the simulated profile, although there are still some differences between the two profiles, especially the squared peaks and valleys on the MASA profile.

6.4.6 Problems with the Multi-Angle Shadow Analysis method

Although the Multi-Angle Shadow Analysis method looked promising, the method soon ran into problems. According to the model shown in Fig. 6-17, L2 must be larger than L1, and L2 must be larger than L1. However, this is not always the case when measuring these shadow widths from the images. In the circumstances, even if an MASA profile can be achieved, the profile will clearly not be reliable. An example of abnormality of L1 and Lr is shown in Table 6-10. The images for the example are shown
in Appendix I. The angle between the light path 1 (Lr1 and Ll1) and the light path 2 (Lr2 and Ll2) is $1.15^\circ$, while the maximum angle difference is $1.2^\circ$, according to Fig. 6-19.

Table 6-10 Abnormality of Ll and Lr

<table>
<thead>
<tr>
<th>Lr2  (pixel)</th>
<th>Lr1  (pixel)</th>
<th>Lr2 - Lr1 (pixel)</th>
<th>Ll2  (pixel)</th>
<th>Ll1  (pixel)</th>
<th>Ll2-Ll1 (pixel)</th>
</tr>
</thead>
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</table>

As seen in Table 6-10, the differences between Lr2 and Lr1 are not always greater than 0. There are some negative values. Ll2 and Ll1 are slightly better, but there is still a zero in the column. Besides, when the difference is only 1 or 2, the measurements become dubious.

One of the reasons for the problem is due to the fact that it is not as easy to identify the location B as to identify the locations A and C in Fig. 6-18. For the illumination shown in Fig. 6-18 (B), the location B is the local minimum (valley) on the first derivative profile, while A and C are the local maxima (peak). There is an example shown in Fig. 6-25. The local minima are clear, but the local maxima are not clear in circled areas. This means that the boundary between the shadow and the illuminated area in a cutter mark valley is not always clear.
In contrast, the intensity profile is very smooth with clear local minima and local maxima, as seen in Fig 6-26.
The intensity profile in Fig. 6-26 is smoothed with a Gaussian filter. The first derivative profile in Fig. 6-25 is not further smoothed. The ambiguous peaks in the circled areas in Fig. 6-25 can be clarified by increasing the cut-off wavelength of the Gaussian filter. Actually, that is how Table 6-10 is obtained. However, over-smoothing due to a large cut-off will make the locations of the local maxima and even the local minima on the first derivative profile less meaningful.

In summary, although the Multi-Angle Shadow Analysis method looks fine in ideal circumstances, it is not robust in reality. This method is built on too many ideal assumptions. The assumption that clear boundaries between shadows and illuminated areas exist is the biggest one.

Furthermore, solving equations Eq. 6-11 to Eq. 6-14 is very time consuming. This is partly due to the fact that the algorithm for solving the equations Eq. 6-11 to Eq. 6-14 discussed in the last section may not be optimum. Some improvements may be done to speed up the equation-solving algorithm. However, it will be difficult to shorten the equation-solving time to a certain level so that the operation can be carried out in real time or near real time.

Another important problem with the Multi-Angle Shadow Analysis method is that it is difficult to implement the method in an online application. The MASA method requires four images to be taken from the both sides of the sample area, and the angle of incidence need to be changed. Doing all these while the wood sample is moving is clearly very difficult, if not impossible.

6.4.7 Conclusions

The Shadow Analysis method is proved to be effective in measurement of cutter mark widths. Although the locations of cutter mark peaks are better identified by the first derivative profile than the intensity profile, no much difference can be made in terms of measuring cutter mark widths. The Multi-Angle Shadow Analysis method, proposed for measuring cutter mark heights along with cutter mark widths, looks fine in theory, but does not work fine in reality. This method relies on too many ideal circumstances, and is not practical in an online application; therefore it is not worth pursuing the direction anymore, especially compared to the Photometric Stereo method that will be discussed in the next chapter.
7. Photometric Stereo method

This chapter describes a new approach to measure cutter marks on machined wood surfaces Photometric Stereo (PS) method. The chapter starts with reviewing reflection models, and shape recovery techniques, including Shape From Shading (SFS) and Photometric Stereo techniques. Then, a two-image Photometric Stereo method tailored to the measurement of cutter marks on wood surfaces is described. After that, experiments are described, which is followed by comparison of the results to those from other methods. In addition, some problems with the two-image photometric method are discussed. After that, a Shape From Shading method is discussed. At the end, the Shadow Analysis method is reviewed from the perspective of surface recovery.

7.1 Reflection from wood surfaces

Wood is an opaque non-uniform dielectric material. When light strikes the wood surface, incident light will be reflected in two manners depicted in Fig. 7-1. A portion of the incident light will be reflected as surface reflection, where the angle of reflection is equal to the angle of incidence, relative to the local surface normal. The other portion of incident light will penetrate the surface-air interface into the subsurface where it will be selectively absorbed or reflected by pigment particles embedded in the medium of the material. After a series of scattering and reflection, the light re-emerge into air as depicted in Fig. 7-1. This type of reflection is known as body reflection, or diffuse reflection. In a word, total reflection from the wood surface comprises surface reflection and body reflection.

![Fig. 7-1 Light reflection from an opaque non-uniform dielectric material](image-url)
Surface reflection, also termed as specular reflection, is precisely described by Fresnel theory. In addition to the angle of reflection being equal to the angle of incidence, the reflected light is an attenuated incident light by a factor determined by the index of refraction for the material and the angle of incidence relative to the surface normal. Detailed descriptions of Fresnel theory can be found in many optics textbooks.

Body reflection, or diffuse reflection, is usually described by Lambert's law, which will be discussed in Section 7.3. Actually, besides Lambert's law, there are some other surface reflectance models, such as Phong's model and Torrance-Sparrow model.

Phong's model is an empirical model, which is based on a linear combination of three components: diffuse, specular, and ambient component [106]. The diffuse component in Phong's model is the same as Lambert's law, while the specular component is determined by an empirical specular reflection coefficient, surface roughness and the angle between the viewing direction and the reflection direction. Torrance-Sparrow model assumes that the surface consists of small, randomly disposed mirror-like facets [107]. The specular reflection from the surface consisting of mirror-like facets is a function of the angles of reflection. The diffuse component results from multiple reflections among the facets and internal scattering.

In addition to the above two models, Wolff and Oren et al. have also advanced some surface reflectance models, which develop some modifications to Lambert's law to make it more accurate and more comprehensive [108-113].

Although all the above-mentioned models may be more accurate, Lambert's law is still the most widely used model in machine vision for surface recovery and other vision techniques. Perhaps, this is because it is relatively easy to implement Lambert's law in machine vision due to its simplicity and effectiveness.

7.2 Definitions

Before diffuse reflection is discussed, some definitions need to be introduced. First of all, the imaging coordinate system. As shown in Fig 7-2, the optical axis of the camera is aligned with the Z-axis of the coordinate system. The surface is perpendicular to the viewing direction. The angle Azimuth is the angle between the X-axis and the light path measured on the X-Y plane. The angle Zenith is the angle between the light path and the viewing direction, i.e., Z-axis. The light source is a point source and far away from the surface so that uniform illumination over the surface can be assumed. The camera is far
away from the surface relative to the size of the surface so that orthographic projection can be assumed.

Secondly, there are two radiometric terms used frequently in the following text. *Irradiance* is the incident radiant power per unit surface area ($Wm^{-2}$). *Radiance* is the power radiated per unit surface area per solid angle in a particular direction ($WSr^{-1}m^{-2}$) from a radiant source. Solid angle $\Omega$ is the angle subtended by a small patch of area $A$ at distance $r$, and defined as $\Omega = \frac{A \cos \theta}{r^2}$, where $\theta$ is the angle between the surface normal and the light. According to the definitions, irradiance is a measure for the energy received on the surface, while radiance is a measure for the energy emitted from an object, which can be a light source or a reflective surface. In the system shown in Fig. 7-2, the surface is the energy emitter from the point of view of the camera; while the light source is the emitter for the surface. For point light sources, another term *Intensity* is more appropriate, as a point does not have an area. *Intensity* is the radiant power per solid angle ($WSr^{-1}$).

### 7.3 Lambert’s law

Since diffuse reflection is usually described with Lambert’s law, the diffuse reflection is also termed as Lambertian reflection, and the surface Lambertian surface. The geometry of Lambertian reflection from a Lambertian surface is illustrated in Fig. 7-2, where

![Fig. 7-2 Geometry of the Imaging Coordinate System and Lambertian Surface](image)
• X-Y plane is the surface reference plane;
• Z-axis is aligned with the normal to the surface,
• (x, y) is a point on the surface,
• N is the normal to the point (x, y);
• L is the vector pointing from the point (x, y) to the light source;
• $\sigma$ is the light zenith, in range $0^\circ$ - $90^\circ$;
• $\tau$ is the light azimuth, in range $0^\circ$ - $360^\circ$;
• $\gamma$ is the angle between L and N.

According to Lambert's law, a perfectly diffuse surface appears equally bright from all viewing angles \[112, 114\]

$$R = \frac{\rho}{\pi} E \cos \gamma = \frac{\rho}{\pi} E (N \cdot L)$$

or in scalar form:

$$R(x, y) = \frac{\rho(x, y)}{\pi} E - p(x, y) \cos \sigma q(x, y) \sin \sigma + \cos \sigma $$

$$\sqrt{p^2(x, y) + q^2(x, y) + 1}$$

Eq. 7-2

where

• $R(x, y)$ is the radiance of the surface at the point $(x, y)$,
• $E$ is the irradiance incident on the surface;
• $\rho(x, y)$ is the diffuse albedo, a coefficient that represents the proportion of light reflected from the point $(x, y)$ with respect to the incident light. $\rho(x, y)$ is only associated with the optical nature of the material at the point $(x, y)$, and irrelevant to the angle of incidence and the angle of viewing.

$$N = \left(\frac{-p}{\sqrt{p^2 + q^2 + 1}}, \frac{-q}{\sqrt{p^2 + q^2 + 1}}, \frac{1}{\sqrt{p^2 + q^2 + 1}}\right)$$

• $L = (\cos \tau \sin \sigma, \sin \tau \cos \sigma, \cos \sigma)$; Clearly, the light in this model must be collimated; otherwise $\sigma$ and $\tau$ will change from point to point on the surface. Consequently, $L$ is the same for every point on the surface.
• $p$ and $q$ are partial derivatives of the surface function $s(x, y)$, i.e. gradients

$$p(x, y) = \frac{\partial s(x, y)}{\partial x}$$

Eq. 7-3
\[ q(x, y) = \frac{\partial s(x, y)}{\partial y} \]  

Eq. 7-4

From Eq. 7-1 and Eq. 7-2, it can be seen that radiance at a surface point \((x, y)\) is associated with the surface gradients at that point, along with illumination orientation, albedo and irradiance of the surface. More importantly, it can be seen that radiance of the surface is not relevant to the viewing direction.

The relationship between radiance of the surface and the surface gradients is nonlinear due to the quadratic part of Eq. 7-2. When the surface is smooth with low slope angles, i.e. \( p \) and \( q \ll 1 \), however, Eq. 7-2 can be approximated by linearisation: \( \sqrt{1 + p^2 + q^2} \approx 1 \), then Eq. 7-2 is reduced to

\[
R(x, y) = \frac{\rho(x, y)}{\pi} E[- p(x, y) \cos \tau \sin \sigma - q(x, y) \sin \tau \sin \sigma + \cos \sigma]
\]

Eq. 7-5

This linearised Lambert's law is often employed for smooth Lambertian surfaces.

### 7.4 Separation of diffuse reflection from specular reflection

In Section 7.1, it is indicated that reflection from a dielectric surface consists of specular reflection and diffuse reflection. In Section 7.3, the relationship between the radiance of a dielectric surface and the surface gradients is established through Lambert’s law. Hence, diffuse reflection must be separated from specular reflection before Lambert’s law can be applied.

Specular reflection and diffuse reflection have different characteristics. Specular reflection maintains more information about the incident light source so that it has the same wavelength of the incident light and the same polarity if the incident light is polarised. In contrast, diffuse reflection contains more information about the material of the surface. Diffuse reflection accounts for the material’s colour, therefore has different wavelength from the incident light. In addition, if the incident light is polarised, diffuse reflection of it will normally lose polarity.

To separate diffuse reflection from specular reflection, the dichromatic reflection model (DRM) is always employed, which also describes light reflection from a dielectric object as the sum of surface (specular) reflection and body (diffuse) reflection [105]:

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In this model, the colour at each image point is the sum of highlight colour \( C_s \) and object colour \( C_b \). The DRM is a simplified model of reflection and it requires some assumptions concerning surface and sensor properties. For example, it assumes that the medium–material interface is neutral, i.e. light reflected at the surface has the same spectral power distribution of the illuminant, that surface reflection is isotropic with respect to rotation about the surface normal, and that pigments are randomly distributed in the material body \([105]\). In \([105]\), a spectroradiometer is used to measure spectral reflection and uses an algorithm described in \([115]\) to estimate the body reflection form veneer surfaces.

There is another approach to separate diffuse reflection from specular reflection. In \([116]\), p-polarised light is used to illuminate the surface, and an s-polariser is used to collect diffuse reflection. Specular reflection cannot go through the s-polariser due to the polarity. Compared to using DRM, using polarised light and a polariser is more relevant to this research.

However, another approach is employed to separate the reflections in this research. Fig. 7-3 shows an obliquely illuminated wood surface. From the surface, the cutter mark waves can be seen due to the regular intensity variations. However, there are some points such as those circled in the figure, which have exceptional intensities, either too bright or too dark compared to adjacent points. The exceptional bright points are clearly specular reflection, while the exceptional dark points are likely to be in shadows. These points are all abnormal points, whose influence may be eliminated by regulating the intensities with some rules.

\[
f_x(\theta_1, \phi_1; \theta_2, \phi_2; \lambda) = f_x(\theta_1, \phi_1; \theta_2, \phi_2)C_s(\lambda) + f_b(\theta_1, \phi_1; \theta_2, \phi_2)C_b(\lambda)
\]

Eq. 7-6

Fig. 7-3 Specular reflection and diffuse reflection

Here a statistic approach is employed. For each column in the image, an average intensity is calculated. Then an intensity zone is set up, which is around the average
intensity with a certain width. The width used is ± 3 times standard deviation of intensities of the column. All points with intensities falling within this zone are accepted, but all points with intensities falling out of the zone are forced to be the average intensity. This approach may be not as good as using a polariser, but it can deal with specular reflection and shadows alike. After applying the algorithm, the artificially made image is shown in Fig. 7-4. As seen in Fig. 7-4, the intensities are more even across the image, and the cutter mark waves look clearer.

![Fig. 7-4 Elimination of effects of specular reflection](image)

### 7.5 Shape recovery techniques

The objective of this research is to measure cutter mark profiles on planed wood surfaces. The problem associated with the objective falls into the scope of shape recovery techniques.

Shape recovery is referred to estimating the shape of a surface from its image(s). Horn [117] expresses this problem with a first-order partial differential equation. Suppose the surface is on the x-y plane, and \( S(x,y) \) is the surface height function; and \( p(x,y) = \frac{\partial S(x,y)}{\partial x} \) and \( q(x,y) = \frac{\partial S(x,y)}{\partial y} \) are the first-order partial derivatives of \( S \), i.e. surface gradients in x and y directions. Then, Horn formulated that

\[
R_m(p(x,y), q(x,y)) = E(x,y)^9
\]

Eq. 7-7

where \( R_m(p,q) \) is termed as reflectance map and \( E(x,y) \) is the irradiance of the image formed on a plane parallel to the surface. The significance of Eq. 7-7 is that it associates the surface gradients with the irradiance of the image(s) so that the surface shape can be

\[^9\text{In [103], the reflectance map is denoted } R(x,y). \text{ In order to differentiate the reflectance map from the radiance } R(x,y) \text{ in Eq. 7-1 and Eq. 7-2, the reflectance map is denoted } R_m(x,y) \text{ here.}\]

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recovered. The key in shape recovery is to establish the relationship between the surface gradients and the image(s), i.e. the reflectance map.

The reflectance map $R_m(p,q)$ is dependent upon the type of the surface and the type of illumination. For Lambertian surfaces, such as the wood surface, the reflectance map is expressed as Eq. 7-1 or Eq. 7-2.

There are two classes of shape recovery techniques. Those that only require one single image are classified as Shape From Shading (SFS) techniques; while those that require multiple images are Photometric Stereo techniques. Here the number of images is also the number of illumination directions. In other words, SFS techniques only require the surface to be illuminated from a single direction, while PS techniques need the surface to be illuminated from different directions for different images.

In Eq. 7-2, there are three unknowns: surface gradients $p$ and $q$, and albedo $\rho$, provided the incident illumination $I_0$ is known, or at least constant. For Photometric Stereo, three images can give three equations, from which the three unknowns can be solved. Woodham [118, 119] developed a technique for calculating the gradients ($p$ and $q$) and reflectance ($\rho$) of a surface from three images with different illumination directions.

At first thought, Shape From Shading is superior to Photometric Stereo due to its simplicity. However, Shape From Shading is not as solid as Photometric Stereo in mathematical terms, and it constitutes a very complicated mathematical problem. In order to solve the three unknowns with one equation, some assumptions and constraints have to be made. There have been a number of SFS techniques developed, which can be divided into four groups: minimization approaches, propagation approaches, local approaches, and linear approaches [120]. Minimization approaches introduce some constraints such as smoothness and brightness, and obtain the solution by minimizing an energy function built from the constraints. Propagation approaches start from a single reference surface point or a set of surface points where the shape is either known or can be uniquely determined, and propagate the shape information across the whole image. Local approaches derive the shape by assuming local surface type, such as approximating the local surface regions by spherical patches. Linear approaches compute the solution based on the linearisation of the reflectance map, as indicated in Eq. 7-5. Thorough reviews on SFS techniques can be found in [120, 114].
Gullon indicates that Shape From Shading is mostly applied to smooth surfaces, while Photometric Stereo is suitable for rough surfaces, such as textures [114].

In addition to Shape From Shading (a single image) and Photometric Stereo (three images or more), there are also some two-image Photometric Stereo techniques. All two-image Photometric Stereo techniques assume a Lambertian surface with constant albedo. As a result, \( \rho \) in Eq. 7-2 does not change with positions, although \( \rho \) is still unknown. Other assumptions that some of two-image Photometric Stereo techniques make include surface topography not changing along one dimension [116], and linear reflectance [121, 122]. Also, most of the two-image Photometric Stereo techniques assume smooth surface and employ some constraints such as integrability and brightness, as some Shape From Shading techniques.

**7.6 Novel two-image Photometric Stereo method for wood surfaces**

Due to cutter marks normally only taking place along one dimension, a planed wood surface can be seen as a corrugated surface if roughness is neglected, as shown in Fig. 7-5. Although there may be surface height variations across the width of the surface, a 2-D surface profile can always be extracted by averaging the 3-D surface. This has been proven with averaging laser profiles in Chapter 4. Actually, as proven in Chapter 4, an averaged profile is more reliable in terms of representing a surface than a single profile.

![Diagram](image.png)

*Fig. 7-5 A 3D surface with cutter marks simplified to a 2D profile with cutter marks*
Suppose the surface height does not change in Y-axis in Fig. 7-5, and if two light sources are located opposite to each other and both along the cutter mark direction, i.e., \( \tau_1 = 180^\circ \) and \( \tau_2 = 0^\circ \), with X-axis aligned with the cutter mark direction, then a two-image Photometric Stereo model is constructed as shown in Fig. 7-6. Light sources 1 and 2 are identical in all respects, and they are located opposite to each other and symmetric around the Z-axis. Two images are to be taken from the surface, with only Light source 1 on and only Light Source 2 on respectively. The annotations in Fig. 7-6 are as follows:

- \( S_n \) is the surface normal, parallel to the Z-axis and the optical axis of the camera;
- \( x \) is a point on the surface (exactly to say, surface profile);
- \( n(x) \) is the normal to the point \( x \);
- \( L_1 \) is the vector pointing from the point \( x \) to Light source 1;
- \( L_2 \) is the vector pointing from the point \( x \) to Light source 2;
- Since light from the Light sources is collimated, \( L_1 \) is the same for the whole surface, and so is \( L_2 \);
- \( \sigma_1 \) and \( \sigma_2 \) are the angles of incidence\(^{10} \), i.e., angles between the surface normal \( S \) and \( L_1 \), and \( S \) and \( L_2 \), these two angles are equal, so they are also annotated with \( \sigma \);
- \( \gamma_1 \) is the angle between the normal \( n(x) \) and \( L_1 \);
- \( \gamma_2 \) is the angle between the normal \( n(x) \) and \( L_2 \).

\[ \text{Camera} \]
\[ S_n \]
\[ \text{Light source 1} \]
\[ L_1 \]
\[ n(x) \]
\[ \sigma_1 \]
\[ \gamma_1 \]
\[ \text{Light source 2} \]
\[ L_2 \]
\[ Z \]
\[ x \]
\[ X \]

Fig. 7-6 Schematic of the two-image Photometric Stereo method

\(^{10}\) In this chapter, the angle of incidence is always referred to as the angle between the light and the surface normal, while in the previous chapters the angle of incidence is referred to as the angle between the light and the surface plane.
Substituting $\tau_1 = 180^\circ$ and $\tau_2 = 0^\circ$ in Eq 7-2 gives

$$R_1(x) = \frac{\rho(x)}{\pi} \frac{p(x) \sin \sigma + \cos \sigma}{\sqrt{p^2(x) + 1}}$$

Eq. 7-8

$$R_2(x) = \frac{\rho(x)}{\pi} \frac{p(x) \sin \sigma + \cos \sigma}{\sqrt{p^2(x) + 1}}$$

Eq. 7-9

Since Light source 1 and 2 are identical and located symmetric to the surface, $E_1 = E_2$. Dividing Eq. 7-8 by Eq. 7-9 gives

$$\frac{R_1(x)}{R_2(x)} = \frac{p(x) \sin \sigma + \cos \sigma}{p(x) \sin \sigma + \cos \sigma}$$

Eq. 7-10

From Eq. 7-10, we have

$$p(x) = \frac{R_1(x) - R_2(x)}{R_1(x) + R_2(x)} \cdot \frac{1}{\tan \sigma}$$

Eq. 7-11

Note that $R_1$ and $R_2$ are radiance of the surface, which are to be measured with the camera in the form of pixel intensities in images. As a result, pixel intensities in images are the data that can be employed to derive the reflection from the surface. The intensity of a pixel in an image is determined by Eq 7-12 [117].

$$I = T \cdot R \cdot \frac{\pi}{4} \left( \frac{d}{f} \right)^2 \cdot \cos^4 \alpha \cdot A \cdot t \cdot c$$

Eq. 7-12

where

- $T$ is the transmission of the lens on the camera;
- $R$ is the radiance of the surface;
- $d$ is the clear aperture of the lens;
- $f$ is the distance between the second principle surface of the lens to the imaging plane;
- $A$ is the pixel area (mm$^2$);
- $t$ is the exposure time,
- $c$ is the ratio of light energy incident on a pixel on the imaging plane to the grey level intensity of the corresponding image pixel;
• \( \alpha \) is the off-axis angle for the pixel on the imaging plane, also for the imaged point on the surface, calculated from

\[
\tan \alpha = \frac{1}{f} \sqrt{x^2 + y^2}
\]

Eq. 7-13

\( x, y \) are coordinates of the point on the imaging plane.

For a specific pair of images taken with the conditions shown in Fig. 7-6, \( T, d, f, A, t, \) and \( c \) are constant. Although \( \alpha \) is not constant, it is identical for the pixel in the two images. Therefore,

\[
\frac{I_1(x) - I_2(x)}{I_1(x) + I_2(x)} = \frac{R_1(x) - R_2(x)}{R_1(x) + R_2(x)}
\]

Eq. 7-14

Consequently, Eq 7-11 becomes

\[
p(x) = \frac{I_1(x) - I_2(x)}{I_1(x) + I_2(x)} \cdot \frac{1}{\tan \sigma}
\]

Eq. 7-15

As such, the surface gradient along X-axis can be derived from \( I_1, I_2, \) and \( \sigma \).

It is assumed in the above that the surface height does not change in Y-axis. Actually, even if it does change, with the orientations of the light sources, i.e. \( \tau_1 = 180^\circ \) and \( \tau_2 = 0^\circ \), effects of \( q(x) \) in Eq 7-2 will be cancelled, as \( \sin(\tau_1) \) and \( \sin(\tau_2) \) are zero.

Strictly speaking, Eq. 7-15 is only applicable to a profile on the surface parallel to the X-axis, and in the circumstances, \( I_1 \) and \( I_2 \) are only a row in the respective images. If the 'adding column by column' algorithm used in the Shadow Analysis method is borrowed, \( I_1 \) and \( I_2 \) become intensity profiles of the whole images, which essentially are kind of averaged profiles. As a result, \( p \) calculated from Eq. 7-15 becomes an averaged gradient profile in fact.

In the above mathematical derivation, there are ideal conditions to be assumed: \( E_1 = E_2, \sigma_1 = \sigma_2, \tau_1 = 180^\circ, \) and \( \tau_2 = 0^\circ \). In reality, it may be very difficult to guarantee the conditions. The problems with misalignment of the light sources will be discussed in Section 7.9.

\( p \) in Eq 7-15 is only determined by the surface itself, and irrelevant to illumination. So any angle of incidence \( \sigma \) should give the same result. From this point of view, it seems
that the angle $\sigma$ can be any value between $0^\circ$ - $90^\circ$. However, when the angle of incidence is close to $90^\circ$, the illumination will make the surface too shadowy. This will compromise the Photometric Stereo method because Lambert's law does not apply to shadowy surfaces.

However, small angles of incidence will cause another problem. The practicability of Eq. 7-15 depends on contrast of $I_1(x)$ and $I_2(x)$, i.e. the contrast of the images. It is a common sense that when the incident light is approximately normal to the surface, the contrast on the image of the surface caused by surface height variations will be very weak, and when the light source moves to the side of the surface, the contrast becomes stronger.

The relationship between the angle of incidence and the consequent contrast is simulated and shown in Fig. 7-7. The simulation is based on the surface shown in Fig. 7-8. In Fig. 7-7, the X-axis is the angle of incidence, which is in range $0^\circ$-$87^\circ$; while the Y-axis is relative surface radiance varying range, which reflects the contrast of the image. As seen in Fig. 7-7, if the relative radiance varying range is considered 1 when the angle of incidence is $87^\circ$, then when the angle of incidence is $0^\circ$, i.e. normal to the surface, the relative radiance varying range falls to approximately 0. This indicates that larger angles of incidence give better contrast, which agrees with the common sense.

There is another reason for larger angles of incidence. That is when the angle $\sigma$ is large enough, it is easy to make $E_1$ and $E_2$ in Eq. 7-8 and Eq. 7-9 approximately uniform across the surface, and therefore easy to make $E_1$ and $E_2$ approximately equal. Making uniform illumination will be further discussed in Section 7.10.
Fig. 7-7 Image contrast vs. the angle of incidence

Fig. 7-8 Simulated surface

Fig. 7-9 Surface image illuminated with a small angle of incidence
7.7 Integration

From Eq. 7-15, surface gradient along X-axis $p$ can be calculated, which is the first derivative of the surface $p(x) = \frac{ds}{dx}$, where the surface shape function $s(x)$ is already reduced to a 2-D profile. In order to get the surface shape function $s(x)$, integration of $p(x)$ is necessary.

Compared to integration for a 3-D surface, integration for a 2-D surface is much easier. So integration techniques, which are mainly developed for 3-D surface integration, are only briefly reviewed. There are two types of integration techniques, local approaches and global approaches [114]. Local approaches start integration with an initial depth and propagate depth values according to a local approximation rule. Some local integration techniques estimate the depth of a point by considering the gradients of two adjacent points; while some consider more points for accuracy. There also have been several global integration techniques developed. Frequency integration is a global integration technique, which is considered simple and most relevant. A 2-D implementation of frequency integration is as follows:

Fourier transformation of $p(x) = \frac{ds}{dx}$ gives

$$P(u) = 2\pi u S(u)$$  \hspace{1cm} \text{Eq. 7-16}

then
\[ S(u) = \frac{P(u)}{2\pi u} \]  
\[ \text{Eq. 7-17} \]

Inverse Fourier transformation of Eq 7-17 gives the surface shape function.

\[ s(x) = F^{-1}(S(u)) \]  
\[ \text{Eq. 7-18} \]

A local integration algorithm for the 2-D surface is also developed. This approach is a propagation integration technique. The procedure for the algorithm is:

1. Suppose \( s(I) = 0 \)
2. \( s(I+1) = s(I) + p(I), I \geq 1 \)
3. Repeat step 2 until the whole surface is recovered.

Experiment shows that frequency integration and propagation integration give very similar results. This is due to the simplicity of only one-dimensional integration involved in this research.

7.8 Experiment

The experimental setup is illustrated in Fig. 7-11. The light sources are composed of a laser, a collimator, and a beam expander. These components, along with the camera, are introduced in Chapter 3. Note that although the two light sources are both shown on, they actually work separately during the acquisition of image 1 and image 2.

![Fig. 7-11 Experimental setup](image)

A number of wood samples have been tested with the Photometric Stereo method. Here only one sample test result is given as an example. More sample test results will be given in the next chapter when measurements obtained with all the methods are compared.
Fig. 7-12 and Fig. 7-13 are two images taken with the method discussed above. The cutter mark pattern on the sample surface is 4-knife cut per revolution with spindle vertical vibration of ±5μm. The cutter mark widths are nominally made 3 mm. In Fig. 7-12, the illumination is from the left hand side; while in Fig. 7-13, the illumination is from the right hand side. The angle of incidence for both images is 87°.

First, apply the algorithm for eliminating specular reflection discussed in Section 7.4. Then, calculate intensity profiles $I_1$ and $I_2$. After that, Eq. 7-15 is used to calculate the gradient function $p$, which is followed by integration with the methods presented in Section 7.7. Finally, a photometric stereo (PS) profile is obtained and plotted in Fig. 7-14, along with a laser profile (LP) measured with the laser profilometer. Also the PS profile is compared to an MASA profile obtained with the MASA method in Fig. 7-15, and also compared to an LS (Laser Sectioning) profile in Fig. 7-16. Note that Y-axes in the three figures are all relative heights. The method with which the relative height is calculated is referred to Chapter 5 and 6. As can be seen in the figures, the PS profile and the LP profile are best fit with each other. The PS profile is generally in accord with the MASA profile except the MASA profile has pointed peaks. However, the PS profile is not in
good accord with the LS profile, especially the first half of the profiles. Relatively, the LS profile is the least reliable among the recovered profiles.

![Figure 7-14 PS profile vs. LP profile](image_url)

**Fig. 7-14 PS profile vs. LP profile**

![Figure 7-15 PS profile vs. MASA profile](image_url)

**Fig. 7-15 PS profile vs. MASA profile**
7.9 Error analysis

7.9.1 Misalignment of the light sources

Several factors regarding misalignment of the light sources can affect the performance of the two-image Photometric Stereo method: (Refer to Fig. 7-6)

- Actual value of the angle \( \sigma \) different from its nominal value
- \( \sigma_1 \) not being equal to \( \sigma_2 \)
- \( \tau_1 \) not being 180° and \( \tau_2 \) not being 0°
- \( E_1 \) not being equal to \( E_2 \)

Among the above factors, the difference between its nominal value and its actual value of angle \( \sigma \) has a clear effect: it will only change the amplitude of the calculated gradient function \( p(x) \), according to Eq 7-15, and the amplitude of the surface shape function after integration. As for other factors, their effects are not straightforward. Therefore, simulations were done to uncover the effects. One of the simulations, which is also the most comprehensive one, is done with following assumptions

- \( \sigma = 80° \)
- \( \Delta \sigma = 5° \), suppose \( \sigma_2 = \sigma \), and \( \sigma_1 = \sigma + \Delta \sigma \)
With these assumptions, Eq 7-8 and Eq. 7-9 become

\[ R_1(x) = E_1 p(x) \frac{-p(x) \cos \tau_1 \sin(\sigma + \Delta \sigma) + \cos(\sigma + \Delta \sigma)}{\sqrt{p^2(x) + 1}} \]

\[ R_2(x) = E_2 p(x) \frac{-p(x) \cos \tau_2 \sin \sigma + \cos \sigma}{\sqrt{p^2(x) + 1}} \]

Eq. 7-19

Eq. 7-20

The procedure for the simulation is:

1. A surface profile with 2 mm cutter marks is simulated, which is referred to as real surface profile.
2. Surface reflection \( R_1(x) \) and \( R_2(x) \) are calculated with Eq 7-19 and Eq. 7-20.
3. Surface gradient function \( p(x) \) of the surface is calculated with Eq. 7-11.
4. Surface shape function \( s(x) \) is calculated by integrating gradient function \( p(x) \), which is referred to as recovered surface profile.

The surface profiles are plotted in Fig. 7-17. The dotted line is the real surface profile, while the solid line is the surface profile recovered with Eq 7-19, Eq 7-20, and Eq. 7-11. It can be seen in the figure that the recovered surface profile has quite different amplitude from the real surface profile. On closer inspection, it is also found that these two profiles have a phase shift of 2.16°. However, the amplitude error and the phase shift do not change the shape of the profile. The correlation coefficient between these two profiles is 1.

In summary, although misalignment of the light sources can introduce amplitude and phase errors, the surface shape will remain the same. This means that cutter mark heights measured with this method may not be accurate; however, the height measurements are proportional to the real heights, and the proportional coefficient can be calibrated by measuring a surface with known cutter marks.
7.9.2 Misalignment of the sample surface with respect to the FOV of the camera

Since the 3-D surface is modelled as a 2-D profile, and the image taken from the surface is also converted to an intensity profile, the problem of misalignment of the surface with respect to the FOV of the camera arises, which is illustrated in Fig. 7-18. Dashed lines represent the cutter marks on a sample ideally aligned under a camera, while solid lines represent the cutter marks on a misaligned sample. The angle $\theta$ is the angle of misalignment.

![Diagram showing misalignment of surface under camera](image_url)
Effects of misalignment of the surface with respect to the FOV of the camera were simulated. The procedure for the simulation is similar to the procedure mentioned in Section 7.9.1. Fig. 7-19 shows a comparison between a real surface profile with 2 mm cutter marks (dotted line) and its corresponding recovered surface profile after the surface is rotated 5°. Clearly, the amplitudes of these two profiles are different; however, there is no phase shift between these two profiles. The correlation coefficient between these two profiles is 1. Similar simulation with 15° rotation of surface gave the similar result.

![Diagram of surface profiles](image)

Fig. 7-19 Effects of misalignment of the surface with respect to the FOV of the camera

Misalignment of this type was also studied on real surfaces. Five misaligned samples with 2 mm cutter marks were imaged with the angle of misalignment from 1° to 5° with respect to an aligned sample. The images are shown in Appendix J. Comparison of profiles from the five misaligned samples and the aligned sample is shown in Fig. 7-20. Table 7-1 shows the correlation coefficients among the six profiles. As seen in the table, the coefficients are not less than 0.94. Actually, by observation of the misaligned sample images shown in Appendix J, it is found that it is easy to discern a misalignment with 2° by the eye. The correlation coefficients for misalignment not more than 2° are even higher, not less than 0.98. Therefore, it is concluded that misalignment of sample surface with respect to the FOV of the camera will not cause much error.
7.10 Applicability of Shape From Shading method

As mentioned before, Shape From Shading method only requires a single image to derive the surface profile. From this point of view, Shape From Shading is simpler to implement than Photometric Stereo. The section explores the applicability of Shape From Shading to wood surfaces.

Suppose we only have one image from the surface with Azimuth $\tau = 180^\circ$, then according to Eq. 7-2, we have

$$R(x, y) = \frac{\rho(x, y)}{\pi} - \frac{\rho(x, y) \sin \sigma + \cos \sigma}{\sqrt{\rho^2(x, y) + q^2(x, y) + 1}}$$
If we further assume that the surface is smooth enough so that \( p \ll 1 \), and \( q \ll 1 \), therefore 
\[
\sqrt{1 + p^2 + q^2} \approx 1,
\]
then Eq. 7-21 becomes

\[
R(x, y) = \frac{\rho(x, y)}{\pi} E[p(x, y) \sin \sigma + \cos \sigma]
\]

Combination of Eq. 7-22 and Eq. 7-12, and reducing the 3-D surface to a 2-D profile, we have

\[
I(x) = T \cdot \frac{\rho(x)}{4} E[p(x) \sin \sigma + \cos \sigma] \left(\frac{d}{f}\right)^2 \cdot \cos^4 \alpha \cdot A \cdot t \cdot c
\]

Annotations are the same as those for Eq. 7-12.

As discussed before, \( T, d, f, A, t \) and \( c \) are constant. \( \alpha \) is the off-axis angle, which is not constant across the FOV. However, \( \alpha \) can be uniquely determined with Eq. 7-13 for each pixel. Consequently, the effects of the off-axis angle can be cancelled by dividing the image intensities at every pixel by \( \cos^4 \alpha \).

Ideally, \( E \) should be constant across the surface, or at least across the surface image area. In reality, however, it is difficult to realise it, especially with the use of laser. \( E \) is the irradiance ( \( Wm^{-2} \)) incident on the surface, which is determined by the radiance ( \( Wm^{-2}Sr^{-1} \)) of the light source. The laser used in this research, like normal diode laser, has a Gaussian profile. In addition, laser beam is projected at a small angle with respect to the surface so that the Gaussian profile is stretched out on the surface, as shown in Fig. 7-21.

The relationship between the surface irradiance profile \( G_s \) and the laser irradiance profile \( G \) is
\[ G_s = G \cdot \cos \theta \]

Eq. 7-24

When the angle \( \theta \) is 85°, \( G_s \) and \( G \) are as shown in Fig. 7-22. Note that due to laser beam being collimated, radiance does not make sense in the circumstances. Instead, irradiance is used to describe the radiant power from the laser. As seen in Fig. 7-22, the surface irradiance over the 40 mm stretched section is almost flat compared to the laser irradiance profile, with a range of only 0.0036 compared to the maximum value of the laser irradiance profile. As a result, it is assumed that \( E \) is uniform over 40 mm range on the surface.

Note that the surface irradiance profile shown in Fig. 7-22 is only applicable to the direction along the length of the surface. In the direction across the width of the sample surface, the surface irradiance profile still has a clear Gaussian profile, as the laser irradiance profile is not stretched in this direction. However, since the PS and the SFS operations only take place along the length of the surface, which is due to the angle \( \tau \) being either 0° or 180°, the Gaussian profile of the surface irradiance across the width of the surface will not cause problems.

![Fig. 7-22 Laser irradiance profile and surface irradiance profile](image)
After the above analysis, there are still two unknown variables left in Eq. 7-23. It is clear that $p$ is solvable only if $\rho$ is assumed constant. So suppose $\rho$ is constant. In this circumstance, Eq. 7-23 can be reduced to

$$I(x) = [p(x)\sin \sigma + \cos \sigma] \cdot C$$

\text{Eq. 7-25}

where $C = T \cdot \frac{\rho}{4} \cdot E \left( \frac{d}{f} \right)^2 \cdot A \cdot t \cdot c$. In addition, $I(x)$ is calculated from the image divided by $\cos^4 \alpha$.

The value of $C$ is not easy to establish, and it is not necessary to do so. If ignoring $C$ in Eq. 7-25, then we have

$$I(x) = p(x) \sin \sigma + \cos \sigma$$

\text{Eq. 7-26}

Here we use $p_c$ to distinguish from $p$ in Eq. 7-25. Then we have

$$p_c(x) = \frac{I(x)}{\sin \sigma} - \frac{1}{\tan \sigma}$$

\text{Eq. 7-27}

From Eq. 7-25, we have

$$p(x) = \frac{I(x)}{C \sin \sigma} - \frac{1}{\tan \sigma}$$

\text{Eq. 7-28}

From Eq. 7-27 and Eq. 7-28, we have

$$p(x) = \frac{p_c(x)}{C} - \frac{C - 1}{C \tan \sigma}$$

\text{Eq. 7-29}

According to Eq. 7-29, $p$ has a linear relationship with $p_c$. It is easy to prove that after integration and normalisation $S$ and $S_c$ will be equal.

Therefore, surface shape function can be derived from a single image with Eq. 7-26 provided all the assumptions are met, i.e. albedo $\rho$ is constant and surface irradiance $E$ is uniform.

Thus single image SFS method is implemented on the image shown in Fig. 7-12. The calculated SFS profile is plotted along the PS profile in Fig. 7-23. The solid line is the PS profile, the dashed the SFS profile. As seen in the figure, the SFS profile is almost
overlapping the PS profile. This result indicates that all the assumptions about albedo $\rho$ and surface irradiance $E$ are met or approximately met. More comparison of PS and SFS will be given in the next chapter.

![Graph showing PS profile vs. SFS profile](image)

**Fig. 7-23 PS profile vs. SFS profile**

### 7.11 Further discussions on the Shadow Analysis method

In the last section, it is found that SFS method almost gives the same result as PS method. Moreover, SFS method is similar to the shadow analysis (SA) method discussed in Chapter 6. So, it is necessary to review the Shadow Analysis method.

#### 7.11.1 Analysis of Shadow Analysis with Lambertian model

The first difference between the SA method and the SFS method is whether or not shadows are involved. The SA method is claimed to require shadows to be made on the surface, from which cutter mark widths can be measured. In [2], Hoffmeister states that 'This illumination with an acute angle of incidence creates shadows of the cut mountains in the cut valleys.' Therefore, a very small angle of incidence with respect to the surface is necessary in the SA method. In contrast, the SFS method is supposed to ignore shadows and therefore avoid making shadows in the first place. This difference gives rise to a question whether shadows are necessary to the SA method.
The essence of the SA method is to associate peaks on the intensity profile to the peaks on the surface profile, or exactly to say, associate peak-to-peak distances on the intensity profile to peak-to-peak distances on the surface profile. Hoffmeister did not give the reasons for the association. However, when considered from the perspective of Lambertian model, the association is reasonable: as shown in Fig. 7-24, in a cutter mark waveform, the normal to the peak towards to the light source has locally the minimum angle with the light vector, therefore has the highest radiance according to Eq. 7-1.

![Fig. 7-24 Angles between light and normal](image)

According to the above analysis, shadows are not necessary for the SA method. In fact, shadows created by a high ridge may very well eclipse an adjacent low ridge, as shown in Fig. 5-12, which is supposed to have negative effects on the SA method. Even if shadows are made on the surface, those areas that are illuminated still comply with Lambertian model and Eq. 7-1 is still applicable on those areas. Actually, most of the images in Chapter 6 were taken with the angle of incidence fairly large. Therefore, it can be assumed that no shadows are involved in those images.

According to Fig. 7-24, the peaks on the intensity profile should be coincident with the peaks on the surface profile. However, this seems to contradict the discussions in Chapter 6 as to the peaks on the derivative profile being coincident with the peaks on the surface profile. The reason for that is because the cutter mark waveform in Fig. 7-24 is idealised. Real cutter marks do not have pointed peaks, but have rounded peaks. This makes the peaks on the intensity profile shift from the peaks on the surface profile.

Fig. 7-25 shows the surface profile measured with the laser profilometer. According to Lambertian model and Lambert’s law, the surface radiance profile is calculated from the surface profile in Fig. 7-25, and plotted in Fig. 7-26 (solid line) along with the surface profile (dashed line). Note that these two profiles are all normalized in order to better make the comparison. From Fig. 7-26, it can be seen that the surface radiance profile and
the surface profile are not in phase, i.e. there is a phase shift between the peaks on the surface radiance profile and the peaks on the surface profile. Essentially, the surface radiance profile is equivalent to the intensity profile calculated according to Hoffmeister's 'adding column by column' algorithm. In contrast, Fig. 7-27 shows the derivative of surface radiance profile vs. the surface profile. The derivative of surface radiance profile is calculated by differentiating the surface radiance profile in Fig. 7-26. This is equivalent to the improved Shadow Analysis method discussed in Chapter 6 Section 6.1. As seen in Fig. 7-27, the X-axis locations of the peaks on the surface radiance changing rate profile are largely coincident with the X-axis locations of the peaks on the surface profile. This proves that the improved shadow analysis algorithm developed in Chapter 6 can better predict the cutter mark peaks.

Table 7-2 shows the comparison of widths measured from the surface profile directly, measured from the radiance profile, and measured from the derivative of radiance profile. As seen in the table, the widths are largely in agreement, but at some points differences are as remarkable as 0.7 mm or 0.5 mm. For the radiance profile and the surface profile, the mean of width differences is 192 μm with standard deviation of 192 μm. For the derivative of radiance profile and the surface profile, the mean of width differences is 121 μm with standard deviation of 89 μm. Both of the SA measurements give some error. This is not surprising because every cutter mark waveform is different, not only in terms of widths and heights, but also in terms of shapes and slopes, which determine the radiance at each point. Accordingly, it can be seen that the SA method is not solid in theory, but may be acceptable if accuracy is not the biggest issue.
Fig. 7-25 Surface profile from sample B3V

Fig. 7-26 Surface radiance profile vs. surface profile (Sample B3V)
7.11.2 Uniform and non-uniform illumination

Another difference between Hoffmeister’s SA method and the SFS method experimented in this chapter is whether non-collimated or collimated light is used. Fig
7-28 is redrawn from Hoffmeister's paper [2]. As shown in Fig. 7-28, the light rays are parallel, so light seems collimated. However, there is a diffusing screen in the light source box, which is supposed to diffuse the light, i.e., make the light non-collimated. Therefore, light rays coming out the light source box could be like those shown in Fig. 7-29. After the diffusing screen, the collimated rays become diffuse, flying in all directions. In addition, only rays flying in the angles between Ray 1 and Ray 2 can pass through the blind.

Fig. 7-28 Configuration of Hoffmeister's test rig [2]

Fig. 7-29 Light rays after the diffusing screen and the blind
This gives rise to a question: how non-collimated light affects the SA method. Essentially, non-collimated light will cause non-uniform irradiance incident on the surface. This problem of non-uniform irradiance will also affect the SFS method, and even the PS method.

Lambert's law expressed in Eq 7-1 is the foundation of the whole chapter. $E$ in the equation is irradiance incident on the surface. Collimated light does not necessarily mean uniform irradiance, as collimated light is usually produced by a laser, which could have a Gaussian profile. As shown in Fig 7-22, however, when the incident angle with respect to the surface is small enough, the irradiance incident on the surface can be approximately uniform. But, for a non-collimated light source, this approximation is hard to justify unless the light source is far way from the surface. Here we simulate the effects on the SA method of surface irradiance with fairly large variations. A surface with the same cutter mark pattern as shown in Fig 7-8 is used. Suppose the irradiance incident on the surface has a Gaussian profile (here only one dimension considered), as shown in Fig. 7-30. Then, the surface radiance, calculated according to Eq. 7-1 with an angle of incidence of 87° and with an assumption of constant albedo $\rho$, is plotted (solid line) in Fig. 7-31. Also plotted (dashed line) in Fig. 7-31 is the surface radiance when the irradiance is constant. As seen in Fig. 7-31, although the new radiance profile (solid line) is distorted compared to the old one (dashed line), the peaks and the valleys are located at the same places in terms of X-axis.

Fig. 7-30 Irradiance with a Gaussian profile
With the variation of irradiance becoming bigger, the distortion of radiance becomes bigger. When the variation is so big that the distortion of radiance profile reaches a critical point, the distortion becomes unacceptable. Fig. 7-32 shows an irradiance profile with a large variation range. Fig. 7-33 shows the radiance originated from the irradiance shown in Fig. 7-32. As can be seen, the first three peaks on radiance profile are easy to be mistaken. However, the ratio of brightest to the darkest in Fig. 7-32 is about 10x. This is very unusual for an illumination scenario, even though the illumination is non-uniform. Variation range of irradiance of non-uniform illumination is normally less than 3x, if one uses a non-collimated light source and does not intend to make a patterned illumination. Therefore, the SA method is robust to non-uniform illumination.
Fig. 7-33 Surface radiance when the irradiance is as in Fig. 7-32

However, the above analysis is only the case for idealized surfaces. For a real surface, there are rounded peaks on the profile. This makes the SA method less robust to non-uniform illumination. Simulation is made on the surface shown in Fig. 7-25, which is a real surface profile measured with the laser profilometer. The simulated irradiance incident on the surface is shown in Fig. 7-34. The calculated surface radiance is shown in Fig. 7-35, along with the surface radiance when irradiance is constant. The locations of the peaks (marked out) on the two radiance profiles are compared in Table 7-3. As seen in the table, although the locations of peaks on these two profiles have differences, these are small, typically 0.1 mm at the most.

When the irradiance becomes what is shown in Fig. 7-36, the effects of non-uniform irradiance become bigger, as shown in Fig. 7-37. The first peak on the solid line becomes ambiguous. The comparison of peak locations is shown in Table 7-4. Clearly, differences between the first columns in Table 7-4 are larger than those in Table 7-3, with the maximum difference being 0.2 mm.

Note that this example is based on a surface with about 3 mm cutter mark widths, and simulation is done with an angle of incidence of 87°. Different surfaces and different incident angles will have different influences on the radiance profile, although the trend is the same.
Fig. 7-34 Irradiance incident on the surface shown in Fig. 7-25

Fig. 7-35 Radiance from the surface shown in Fig. 7-25 when irradiance is as shown in Fig. 7-34
Table 7-3 Comparison of locations of peaks in Fig. 7-35

<table>
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<tr>
<th>Peaks on dashed line μm</th>
<th>Peaks on solid line μm</th>
<th>Differences μm</th>
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<tr>
<td>37179</td>
<td>37152</td>
<td>27</td>
</tr>
</tbody>
</table>

Fig. 7-36 Irradiance incident on the surface shown in Fig. 7-25
Fig. 7-37 Radiance from the surface shown in Fig. 7-25 when irradiance is as shown in Fig. 7-36

Table 7-4 Comparison of locations of peaks in Fig. 7-37

<table>
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<th>Peaks on dashed line µm</th>
<th>Peaks on solid line µm</th>
<th>Differences µm</th>
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</table>

Based on the above, it is concluded that non-uniform irradiance incident on the surface almost does not affect the SA method on idealized surfaces, but will more or less
affect the SA method on real surfaces. Therefore, when applying the SA method, illumination should be made as uniform as possible in order to keep error in an acceptable range.

### 7.12 Conclusions

Reflection from the wood surface can be considered compliant to Lambertian model and Lambert’s law. Based on this, the two-image Photometric Stereo method proposed in this chapter for measuring cutter marks on wood surfaces has a solid theoretical foundation, and has proven viable in the experiments. Furthermore, if some assumptions on the surface and the illumination, such as constant albedo and surface irradiance, are met, Shape From Shading method can be used to replace the two-image Photometric Stereo method for its simplicity of only a single image needed.

The Shadow Analysis (SA) method can be explained with Lambertian model and Lambert’s law. Since the SA method only studies the intensity profile, the surface profile cannot be achieved, as it needs integration of the intensity profile to get the surface profile. However, cutter mark widths can be reasonably measured from the intensity profile. This can also be explained with Lambertian model and Lambert’s law.
8. Comparison of profiles from various methods

This chapter is aimed at comparing various methods that have been studied in the previous chapters. The methods to be compared include the laser profilometry, which is always used as a reference, the Light Sectioning method, the Photometric Stereo method, and the single-image Shape From Shading method. Since the Shadow Analysis method cannot produce surface profiles, this method is not included in the comparison. In addition, although the Multi-Angle Shadow Analysis method can produce surface profiles in theory, in reality, this method has many problems, as discussed in Chapter 6. As a result, the Multi-Angle Shadow Analysis method is not included in this chapter either.

The comparison of various methods is conducted in terms of surface profiles, including visual comparison and correlation coefficients. The surface profiles are all normalised so that they are comparable. The process of normalisation is referred to Chapter 5 and 6.

Three types of wood samples are selected: beech, oak, and ramn. For each type of wood, five samples are made with cutter mark widths of 1 mm, 1.5 mm, 2 mm, 2.5 mm, and 3 mm respectively. However, only samples with cutter mark widths of 1.5 mm, 2 mm, and 2.5 mm are compared.

Information on how the samples are generated is referred to Chapter 3. However, there is one point worth noting. By using the test rig built by Hynek [96], samples can be cut with wanted cutter mark widths. Due to various reasons, however, the wanted cutter mark width is only a nominal figure, although the actual figure will not deviate too much. From the perspective of this research, cutter mark width deviations of this kind do not matter, provided the test rig is working properly. Therefore, no efforts were made to find out the accuracy of the cutting rig or of cutter mark widths on the cut samples.

Surfaces with cutter mark widths of 3 mm are considered coarse surfaces. It is assumed that comparison of samples with cutter mark widths > 2.5 mm will be good provided comparison of samples with cutter mark width of 2.5 mm is good. Therefore, no comparison of samples with cutter mark width of 3 mm is conducted in this chapter.

Comparison of samples with cutter mark width of 1 mm gives very poor results. When the cutter mark width is 1 mm, the cutter mark height is only about 2 μm (cut with a 60 mm cutterhead). In this circumstance, waviness portion of the surface texture is
almost impossible to reasonably separate from roughness portion. In fact, in this circumstance, no method involved in this research can be seen as accurate enough to be the reference. Cutter mark width of 1.5 mm may be a limit to all the methods discussed in this thesis.

In the following sections, the following annotations will be used.

- PS: Photometric Stereo profile
- SFS: Shape From Shading profile
- LS: Light Sectioning profile
- LP: Laser Profilometer profile

Comparison is conducted in three sections. In Section 8.1, PS profiles are compared to LP profiles, with LP profiles used as reference profiles. In Section 8.2, LS profiles are compared to LP profiles, also with LP profiles used as reference profiles. These two sections are aimed to assess the Photometric Stereo method and the Light Sectioning method respectively. In Section 8.3, PS profiles are compared to SFS profiles. For each PS profile, there are two SFS profiles, one with light coming from the left, and the other with light coming from the right. This section is intended for assessing the similarity between the PS profile and corresponding SFS profiles.

At the end of the chapter, in order to give a overall view of comparison of all kinds of profiles, all the correlation coefficients between compared profiles in this chapter are put into a single table.

**8.1 Photometric Stereo profile vs. Laser Profilometer profile**

In this section, the PS profiles are compared to the LP profiles sample by sample in Fig 8-1 to Fig. 8-9, which are followed by Table 8-1 listing all the PS-LP correlation coefficients.

In the following figures, the ‘coef’ on the upper-left corner is the correlation coefficient calculated from the two profiles plotted. The algorithm is referred to in Chapter 4. Besides, the X-axis of the figures is in mm, while the Y-axis is relative heights, i.e. normalised heights. The process of normalisation is referred to in Chapter 5 and 6. All these denotations will be used throughout this chapter.
Fig. 8-1 PS profile vs. LP profile from sample B2.5

Beech sample with 2.5 mm cutter marks

coef = 0.94

Fig. 8-2 PS profile vs. LP profile from Sample B2
Beech sample with 1.5 mm cutter marks

![Graph showing PS profile vs. LP profile from sample B1.5]

Fig. 8-3 PS profile vs. LP profile from sample B1.5

Ramin sample with 2.5 mm cutter marks

![Graph showing PS profile vs. LP profile from sample R2.5]

Fig. 8-4 PS profile vs. LP profile from sample R2.5
The profiles in Fig. 8-5 present an uncharacteristic surface compared to the majority of the other samples. There are two reasons for that. The first reason is that when this sample was being cut, spindle vertical vibration of ±3μm was stimulated intentionally. The cutter mark width of this sample is about 2 mm, and the cutter mark height, if no spindle vibration exists, is about 8 μm. Therefore, the stimulated spindle vibration amplitude is a little too large to the cutter mark pattern so that some of the cutter mark peaks are chopped off.

Another reason is supposedly related to the inappropriate clamping design of the cutting machine. The layout of clamping design is shown in Section 3.7. Because the clamping force is exerted on the side of the sample opposite to the side on which the sample is cut, there could be clearance between the sample bottom surface on the cutting side and the X-Y table top surface. As a result, when the sample is being cut, the cutter tip pushes the sample downwards periodically, stimulating another vibration. The effect of this vibration on the surface is more difficult to predict.

The above analysis also applies to Fig. 8-14, Fig. 8-27 and Fig. 8-28.
Ramin sample with 15 mm cutter marks

![Graph of Ramin sample with 15 mm cutter marks](image)

Fig. 8-6 PS profile vs. LP profile from sample R1.5

Oak sample with 25 mm cutter marks

![Graph of Oak sample with 25 mm cutter marks](image)

Fig. 8-7 PS profile vs. LP profile from sample O2.5
Oak sample with 2 mm cutter marks

Fig. 8-8 PS profile vs. LP profile from sample O2

Oak sample with 1.5 mm cutter marks

Fig. 8-9 PS profile vs. LP profile from sample O1.5
All the PS-LP correlation coefficients are also listed in Table 8-1.

### Table 8-1 PS-LP correlation coefficients

<table>
<thead>
<tr>
<th>Sample</th>
<th>PS-LP correlation coefficient</th>
</tr>
</thead>
<tbody>
<tr>
<td>B2 5</td>
<td>0.94</td>
</tr>
<tr>
<td>B2</td>
<td>0.86</td>
</tr>
<tr>
<td>B1 5</td>
<td>0.82</td>
</tr>
<tr>
<td>R2 5</td>
<td>0.80</td>
</tr>
<tr>
<td>R2</td>
<td>0.94</td>
</tr>
<tr>
<td>R1 5</td>
<td>0.88</td>
</tr>
<tr>
<td>O2 5</td>
<td>0.83</td>
</tr>
<tr>
<td>O2</td>
<td>0.88</td>
</tr>
<tr>
<td>O1 5</td>
<td>0.83</td>
</tr>
</tbody>
</table>

In general, the PS profiles are in very good agreement with the LP profiles, with the correlation coefficients all higher than 0.8. It was assumed that PS profiles from samples with coarse cutter marks would have higher correlation coefficients with their corresponding LP profiles than those from samples with finer cutter marks. However, this is not always the case. There must be some random factors in the measurement and processing, which cause the deviation from the assumption. Nevertheless, based on the comparison, it would be reasonable to conclude that the Photometric Stereo method is effective and robust.

### 8.2 Light Sectioning profile vs. Laser Profilometer profile

In this section, the LS profile of each sample is compared to its LP profile in Fig. 8-10 to Fig. 8-18 respectively. All the LS-LP correlation coefficients are also listed in Table 8-2.
Beech sample with 25 mm cutter marks

Fig. 8-10 LS profile vs. LP profile from sample B2.5

Beech sample with 2 mm cutter marks

Fig. 8-11 LS profile vs. LP profile from sample B2
Fig. 8-12 LS profile vs. LP profile from sample B1.5

Fig. 8-13 LS profile vs. LP profile from sample R2.5
Fig. 8-14 LS profile vs. LP profile from sample R2

Fig. 8-15 LS profile vs. LP profile from sample R1.5
Fig. 8-16 LS profile vs. LP profile from sample O2.5

Fig. 8-17 LS profile vs. LP profile from sample O2
All the LS-LP correlation coefficients are listed in Table 8-2.

**Table 8-2 LS-LP correlation coefficients**

<table>
<thead>
<tr>
<th>Sample</th>
<th>LS-LP correlation coefficient</th>
</tr>
</thead>
<tbody>
<tr>
<td>B2 5</td>
<td>0.87</td>
</tr>
<tr>
<td>B2</td>
<td>0.27</td>
</tr>
<tr>
<td>B1 5</td>
<td>0.51</td>
</tr>
<tr>
<td>R2 5</td>
<td>0.65</td>
</tr>
<tr>
<td>R2</td>
<td>0.50</td>
</tr>
<tr>
<td>R1 5</td>
<td>0.73</td>
</tr>
<tr>
<td>O2 5</td>
<td>0.72</td>
</tr>
<tr>
<td>O2</td>
<td>0.85</td>
</tr>
<tr>
<td>O1 5</td>
<td>0.82</td>
</tr>
</tbody>
</table>

The above LS-LP comparisons do not indicate a clear correlation between the LS profiles and the LP profiles. The correlation coefficients can be as good as the one in Fig. 8-10 (0.87), can also be as bad as the one in Fig. 8-11 (0.27). Although some LS-LP
comparisons, such as in Fig. 8-14, give a correlation coefficient of 0.5, the LS profile is almost totally misleading, if not totally wrong. On the contrary, the comparison in Fig. 8-11 indicates better similarity between the LS and the LP, although the correlation coefficient is down to 0.27. In more comparisons, the LS profiles have either some peaks missing or some added peaks, compared to the corresponding LP profiles. It is also found that light sections from coarse samples (large cutter mark widths) do not necessarily give higher correlation coefficients than those from finer samples (small cutter mark widths).

In Chapter 5, it is only discussed that the LS profiles are likely to give large error on surface heights. According to the comparison in this section, it is found that the LS profiles can sometimes give large error on cutter mark widths as well. This inevitably results in a conclusion that the Light Sectioning method is not robust, especially when compared to the Photometric Stereo method. This conclusion is not completely surprising because the Light Sectioning method is based on two profiles (two edges of a single light section) while the Photometric Stereo method is based on up to hundreds of profiles.

8.3 Photometric Stereo profile vs. Shape From Shading profile

In this section, the PS profile of each sample is compared to its SFS profiles. Since one PS profile is obtained from two images, one PS profile can have two corresponding SFS profiles: one SFS profile obtained from the image with light coming from the left hand side, the other obtained from the image with light coming from the right hand side. Fig. 8-19 to Fig. 8-36 are the PS-SFS comparisons made sample by sample. Also, Table 8-3 lists all the PS-SFS correlation coefficients.
Beech sample with 2.5 mm cutter marks

Fig. 8-19 Sample B2.5 PS vs. SFS with light from the left

Beech sample with 2.5 mm cutter marks

Fig. 8-20 Sample B2.5 PS vs. SFS with light from the right
Fig. 8-21 Sample B2 PS vs. SFS with light from the left

Fig. 8-22 Sample B2 PS vs. SFS with light from the right
Beech sample with 15 mm cutter marks

coeff = 0.66

Fig. 8-23 Sample B1.5 PS vs. SFS with light from the left

Beech sample with 15 mm cutter marks

coeff = 0.86

Fig. 8-24 Sample B1.5 PS vs. SFS with light from the right
Ramin sample with 25 mm cutter marks

coef = 0.54

---

PS profile
SFS(left) profile

Relative height

mm

Fig. 8-25 Sample R2.5 PS vs. SFS with light from the left

Ramin sample with 25 mm cutter marks

coef = 0.8

---

PS profile
SFS(right) profile

Relative height

mm

Fig. 8-26 Sample R2.5 PS vs. SFS with light from the right
Fig. 8-27 Sample R2 PS vs. SFS with light from the left

Fig. 8-28 Sample R2 PS vs. SFS with light from the right
Fig. 8-29 Sample R1.5 PS vs. SFS with light from the left

Fig. 8-30 Sample R1.5 PS vs. SFS with light from the right
Fig. 8-31 Sample 0.25 PS vs. SFS with light from the left

Fig. 8-32 Sample 0.25 PS vs. SFS with light from the right
Fig. 8-33 Sample O2 PS vs. SFS with light from the left

Fig. 8-34 Sample O2 PS vs. SFS with light from the right
Fig. 8-35 Sample O1.5 PS vs. SFS with light from the left

Fig. 8-36 Sample O1.5 PS vs. SFS with light from the right
Table 8-3 PS-SFS correlation coefficients

<table>
<thead>
<tr>
<th>Sample</th>
<th>PS-SFS(left) correlation coefficients</th>
<th>PS-SFS(right) correlation coefficients</th>
</tr>
</thead>
<tbody>
<tr>
<td>B2 5</td>
<td>0.91</td>
<td>0.94</td>
</tr>
<tr>
<td>B2</td>
<td>0.92</td>
<td>0.95</td>
</tr>
<tr>
<td>B1 5</td>
<td>0.66</td>
<td>0.86</td>
</tr>
<tr>
<td>R2 5</td>
<td>0.54</td>
<td>0.8</td>
</tr>
<tr>
<td>R2</td>
<td>0.93</td>
<td>0.73</td>
</tr>
<tr>
<td>R1 5</td>
<td>0.94</td>
<td>0.75</td>
</tr>
<tr>
<td>O2 5</td>
<td>0.89</td>
<td>0.90</td>
</tr>
<tr>
<td>O2</td>
<td>0.98</td>
<td>0.97</td>
</tr>
<tr>
<td>O1 5</td>
<td>0.93</td>
<td>0.86</td>
</tr>
</tbody>
</table>

Generally speaking, the PS profiles match both the SFS (left) and SFS (right) profiles well. However, some matches are not so good, such as PS-SFS (left) of sample R2 5 (0.54), and PS-SFS (left) of sample R1.5 (0.4). This may be explained by that the albedo on those samples is not constant. But this explanation is not very convincing. As a result, whether the SFS method can replace the PS method in terms of measuring surface profiles with reasonable disparities still needs more studies.

8.4 Comparison of all kinds of profiles

For the sake of a summary view of the comparison made in this chapter, all the correlation coefficients between compared profile pairs are listed in Table 8-4, which is actually a combination of Table 8-1 to Table 8-3.

Table 8-4 Correlation coefficients of all kinds of profiles

<table>
<thead>
<tr>
<th>Sample</th>
<th>PS-LP correlation coefficient</th>
<th>LS-LP correlation coefficient</th>
<th>PS-SFS(left) correlation coefficients</th>
<th>PS-SFS(right) correlation coefficients</th>
</tr>
</thead>
<tbody>
<tr>
<td>B2 5</td>
<td>0.94</td>
<td>0.87</td>
<td>0.91</td>
<td>0.94</td>
</tr>
<tr>
<td>B2</td>
<td>0.86</td>
<td>0.27</td>
<td>0.92</td>
<td>0.95</td>
</tr>
<tr>
<td>B1 5</td>
<td>0.82</td>
<td>0.51</td>
<td>0.66</td>
<td>0.86</td>
</tr>
<tr>
<td>R2 5</td>
<td>0.80</td>
<td>0.65</td>
<td>0.54</td>
<td>0.8</td>
</tr>
<tr>
<td>R2</td>
<td>0.94</td>
<td>0.50</td>
<td>0.93</td>
<td>0.73</td>
</tr>
<tr>
<td>R1 5</td>
<td>0.88</td>
<td>0.73</td>
<td>0.4</td>
<td>0.75</td>
</tr>
<tr>
<td>O2 5</td>
<td>0.83</td>
<td>0.72</td>
<td>0.89</td>
<td>0.90</td>
</tr>
<tr>
<td>O2</td>
<td>0.88</td>
<td>0.85</td>
<td>0.98</td>
<td>0.97</td>
</tr>
<tr>
<td>O1 5</td>
<td>0.83</td>
<td>0.82</td>
<td>0.93</td>
<td>0.86</td>
</tr>
</tbody>
</table>
As seen in Table 8-4, the PS-LP correlation is better than the LS-LP correlation for each sample. The Laser Profilometer (LP) profile is used as reference throughout the research. Therefore, it is clear that the Photometric Stereo method performs much better than the Light Sectioning method.

The PS-SFS correlations (the last two columns in Table 8-4) do not give a clear trend. Sometimes, the correlations are very good (such as B2.5), but sometimes they are not so good (such as R1.5). This finding makes using one-image-based Shape From Shading method to measure cutter marks on planed wood surfaces highly dubious. However, this may be worth further studies in the future research.
9. Conclusions

This research is aimed at finding an appropriate machine vision method for measuring cutter marks on machined wood surfaces. Three machine vision methods have been investigated: the Light Sectioning method, the Shadow Analysis method, and the Photometric Stereo method.

Before these machine vision methods are investigated, a laser profilometer is tested for its feasibility of measuring cutter marks on wood surfaces. The feasibility of this profilometer in measuring cutter marks on machined wood surfaces relies on averaging multiple surface profile traces. A single profile traced from the surface of wood can be very misrepresentative. This is due to roughness components (random in nature) of wood surface texture usually having larger amplitude than waviness components (periodic in nature). In theory, the more surface traces to be averaged, the better the final surface profile represents the surface in terms of waviness. However, obtaining a large number of traces can be very time consuming; and when the number of traces reaches a certain value, more traces will only marginally affect the final profile. Therefore, 25 to 50 traces are recommended when the profilometer is used to measure cutter marks on machined wood surfaces.

The laser profilometer may possibly be implemented for in-process applications. But clearly, multiple surface profiles are not easy, if not totally impossible, to trace in-process, especially when up to 50 traces are considered. However, due to the high accuracy and reliability of the instrument, when used in connection with the averaging algorithm, surface profiles measured off-line with the laser profilometer are considered reliable. Therefore, the instrument is used throughout the research as a reference.

The Light Section method is proved to be feasible to measure cutter mark widths to some extent, but cutter mark heights cannot be reliably measured with the method. This is mainly due to the fact that surface height variations not only take place along the feed direction (the first surface height detail), but also take place perpendicularly to the feed direction (the secondary surface height detail) on the surface. The secondary surface height detail also renders the Light Sectioning method unsuitable for cutter mark widths less than 1.5 mm when the surface is cut with a 60 mm cutterhead. Due to the same reason, the Differential Light Sectioning method does not give reliable results in surface height measurements.
The performance of the Light Sectioning method may be improved by projecting multiple laser lines on the surface. However, projecting many laser lines, say more than 10 lines, onto the surface is not practical with the current technology.

The Shadow Analysis method has been proved by some previous research to be effective in measuring cutter mark widths. The algorithm used in the previous research is essentially based on the intensity profile computed from the image by ‘adding intensity values column by column’. In contrast, the algorithm proposed and tested in this research is based on the first derivative of the intensity profile. Experiments indicate that the proposed algorithm predicts locations of cutter mark peaks better than the previous algorithm, although there are only marginal differences between the cutter mark widths obtained with the two algorithms.

Theoretically, the Multi-Angle Shadow Analysis method can measure cutter mark heights along with cutter mark widths. However, the method has many practical problems. One of the problems is that measurement of shadow widths from the images is less reliable than measurement of cutter mark widths. This problem makes the computed surface profile subject to suspicion. Another problem is that this method involves such intensive computation that it can take a modern PC up to 10 minutes to get a surface profile. With this kind of time-consuming computation, it is hard to implement the method in-process. Last but not the least, it is not easy to take 4 images from the same area on the surface with 4 different illumination conditions respectively when the sample is moving rapidly.

The most promising solution to measuring cutter mark profiles comes with the two-image Photometric Stereo method. A foundation of the method is that the wood surface is looked upon as Lambertian surface, and the intensity of reflection from a point on such a surface is solely determined by the intensity of incident light and the angle between the incident light and the local normal to the surface point. Another foundation of the method is that due to cutter marks being directional, a 3-D surface topography can be simplified to a 2-D surface profile. Based on these principles, a surface profile can be extracted from two images taken from the surface illuminated with the same light source but from two opposite directions. This method is well established theoretically, and fairly feasible practically. Among all the methods studied in the research, measurement results from the two-image Photometric Stereo method are best correlated to the results from the laser
profilometer. When the cutter mark width is not less than 1.5 mm (made by a 60 mm cutterhead), measurement results of the two-image Photometric Stereo method are fairly reliable, and the reliability increases as the cutter mark width increases. However, when the surface becomes too smooth, i.e. cutter mark widths < 1.5 mm (made by a 60 mm cutterhead), the two-image Photometric Stereo method almost does not work.

With some assumptions on the surface and the lighting conditions, the two-image Photometric Stereo method may be replaced by the one-image Shape From Shading method. Experiments show that some of the surface profiles measured with the one-image Shape From Shading method agree with the corresponding profiles measured with the two-image Photometric Stereo method, but some of them do not. The inconsistency may be because some of the assumptions made for the one-image Shape From Shading method are not reasonable. Further studies are needed to examine the assumptions.
10. Future Work

After three years work of exploring several machine vision methods for measuring cutter marks on machined wood surfaces, some conclusions have been drawn. However, there is still some work yet to do before the technique becomes mature enough to be implemented in industry.

Firstly, as mentioned at the end of the last chapter, whether the one-image Shape From Shading method can work as well as the two-image Photometric Stereo method is still not clear. If the one-image Shape From Shading method works, then the implementation of the technique will be much simplified in terms of both hardware and software alike. Therefore, this method is worth further studies.

The biggest uncertainty with the one-image Shape From Shading method is whether albedo of wood surface is constant or only varies in such a small range that its effects can be omitted. To resolve this uncertainty, albedos need to be measured point by point across an area of wood surface so that an albedo map can be generated, from which further work can be done. In order to achieve the albedo map, an appropriate method or technique must be identified for measuring albedos point by point.

Secondly, although the research has been carried out with in-process measurement in mind, only static samples have been tested. Therefore, future work should focus on testing moving samples no matter whether the two-image Photometric Stereo method or the one-image Shape From Shading method is used.

The first difficulty envisioned for testing moving samples is image blurring due to sample movement. This clearly needs fast imaging techniques, such as fast imagers and strobe lighting. However, fast imaging will not be a big problem, as the imaging technology has been advancing rapidly, and there have been a lot of fast imaging applications, which deal with objects moving much faster than the wood workpiece feeding.

For the two-image Photometric Stereo method, there is a problem that needs more attention: if two images have to be taken subsequently while the sample is moving, the common area in the two images that covers the same area on the sample surface has to be identified. Clearly, ensuring the two images cover the same area on the surface is a prerequisite for the two-image Photometric Stereo method. To address this problem, an
encoder may be employed so that the distance over which the sample moves between the two shots can be measured. Then, the common area in the two images can be identified accordingly.

Finally, no matter whether the two-image Photometric Stereo method or the one-image Shape From Shading method is selected, the selected method should be further tested on a real woodworking machine, as that is the only way that the robustness of the selected method can be verified.
References


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55. D. L. DoVoe, "An optical area-scattering based approach for the measurement of surface roughness formed during machining," Institute for systems research, University of Maryland, 1993


103. X. Zhao, *Study on measurement of wood surface roughness by computer vision*, Journal of Northeast Forest University 3 (1992), no. 1, 75-81.
104 X. Zhao, X. Zhang and X. Qiang, Preliminary study on measurement of coarse surface roughness by computer vision, Proceedings of the SPIE - The International Society for Optical Engineering 2101 (1993), 1064-1068.


Appendix A Trochoid and cutter tip's locus of rotary machining process

A trochoid is the locus of a point at a distance $b$ from the center of a circle of radius $a$ rolling on a fixed line. A trochoid has parametric equations

$$x = a \cdot \theta - b \cdot \sin \theta \quad \text{Eq. A-1}$$

$$y = a - b \cdot \cos \theta \quad \text{Eq. A-2}$$

If $b < a$, the trochoid is known as a curtate cycloid, if $b = a$, it is a cycloid, and if $b > a$, the curve is a prolate cycloid.

The cutter tip's locus in the rotary machining process can be expressed as below, where $f$ is the feed rate, $\omega$ is the angular velocity of the cutter, and $r$ is the cutting radius

$$x = f \cdot \frac{\theta}{\omega} - r \cdot \sin \theta \quad \text{Eq. A-3}$$

$$y = r - r \cdot \cos \theta \quad \text{Eq. A-4}$$
Compared to Eq A-1 and Eq. A-2, it appears that Eq. A-3 and Eq. A-4 do not define a trochoid, which requires

\[ y = \frac{f}{\omega} - r \cdot \cos \theta \]

Eq. A-5

However, substituting Eq A-5 with Eq A-4 will only make the curve shift vertically, while the shape of the curve will remain. As a result, the cutter tip’s locus in the rotary machining process is still a trochoid. Theoretically, which type of trochoid the locus forms depends on the parameters of cutting radius \( r \), feed rate \( f \), cutter’s angular velocity \( \omega \). When \( f/\omega = r \), the curve is a cycloid; when \( f/\omega > r \), the curve is a curtate cycloid, and when \( f/\omega < r \), the curve is a prolate cycloid. In practice, however, it is usually that \( f/\omega < r \), so the curve is usually a prolate cycloid.
Appendix B StockerYale laser
Final quality control report and CDRH compliance checklist

Customer
- **Company**: FIRSTSIGHT VISION LIMITED
- **P.O. number**: P0R009433

Product
- **Model**: MFL-501-570-5-15°
- **Serial number**: 290903137
- **Class CDRH**: II (with structured light head)

Performance

<table>
<thead>
<tr>
<th>Wavelength</th>
<th>Laser power</th>
<th>Current</th>
</tr>
</thead>
<tbody>
<tr>
<td>675.2nm</td>
<td></td>
<td>50 mA</td>
</tr>
</tbody>
</table>

Safety check
- Collectable power of structured light projector within class limit (section 1040.10 (3) (1) of 21 CFR)
- Emission indicator functions
- Beam attenuator attached
- Warning logotype affixed
- Aperture label affixed
- ID / Certification label affixed
- Instruction manual enclosed

Class IIIb only
- Key not removable at "ON" N/A
- Key switch "OFF" prevents lasing N/A
- No lasing without remote connector N/A
- Emission indicator lit 7 seconds prior N/A

Quality check
- [x] Burn in 24 hours
- [x] Overvoltage protection checked (lasing up to 7.4 Volts)
- [x] Fan angle 15°
- [x] Reverse polarity protection checked
- [x] Laser aligned
- [x] Laser focused
- [x] Laser cleaned

Special quality control for: FIRSTSIGHT VISION LIMITED
- Reference#: 913-020850
- Output power after optic: 3.5 mW
- Working distance: 185 mm

Checked by: [Signature]
Date: 29-Sep-03
Firstsight Vision
MFL-670-5-15-185mm
Line thickness @ working distance 185 mm
Tube#: V359
S/N: 240703137
BeamScope-P5 v5.2Z, 5-17-00 : File name = FIRSTSGT.DAT
Appendix C RS laser (RS no: 194-026)
This data sheet covers the following items:

<table>
<thead>
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<th>Device</th>
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<td>194-004</td>
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<td>3mW modulating</td>
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<tr>
<td>3mW wide angle line generator</td>
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<tr>
<td>Single standard lens</td>
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<td>Line generator lens</td>
<td>194-054</td>
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<tr>
<td>Line generator lens w/o angle</td>
<td>213-3629</td>
</tr>
<tr>
<td>Laser diode holder</td>
<td>213-3641</td>
</tr>
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</table>

Introduction
These devices have been designed as complete laser diode systems for original equipment manufacturer (OEM) use and although their output powers have been set in accordance with BS(EN)60825, they are not certified lasers as defined in the specification. When incorporated in a piece of equipment it may be necessary for additional safety features to be added before equipment complies fully with the standard. Read BS(EN)60825 before using any of these products.

Continuous wave lasers Beta CW series

General characteristics

<table>
<thead>
<tr>
<th>Parameter</th>
<th>111-346</th>
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<th>194-032</th>
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<td>1.5</td>
<td>1.5</td>
<td>mW</td>
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<tr>
<td>Typical power output stability (@20°C)</td>
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<td></td>
<td></td>
<td>%</td>
</tr>
<tr>
<td>Typical power output temperature dependence</td>
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<td></td>
<td></td>
<td></td>
<td>°C</td>
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<td>Operating voltage (V)</td>
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<td></td>
<td>Volts</td>
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<td>Typical operating current at maximum voltage (mA)</td>
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<td>25 - 50</td>
<td>25 - 50</td>
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<td>mA</td>
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<td>&gt;4</td>
<td></td>
<td></td>
<td>Hz</td>
</tr>
<tr>
<td>Mean time to failure (MTTF) @ 30°C</td>
<td>4,500</td>
<td>80,000</td>
<td>20,000</td>
<td>32,000</td>
<td>Hours</td>
</tr>
<tr>
<td>Connections</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Red lead</td>
<td>+ve supply</td>
<td></td>
<td></td>
<td></td>
<td>Volts</td>
</tr>
<tr>
<td>Black lead</td>
<td>-</td>
<td>-ve supply</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Green lead</td>
<td>0</td>
<td>0</td>
<td></td>
<td></td>
<td>Volts</td>
</tr>
<tr>
<td>Blue lead</td>
<td>-</td>
<td>TTL disable</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Description
These laser modules consist of a laser diode, lens and driver circuit housed in a metal case. The module body is electrically isolated. Electrical connections are made via flying leads. The lens is a single element of high refractive index glass which produces a high quality collimated beam over a long distance. Its position can be adjusted to bring the beam to a focused spot using the special key provided. The Beta CW and TX series standard collimating lens may be replaced by a line generating lens which produces a fan shaped beam that can be focused to a fine, straight line, (RS stock no. 194-032) is supplied with a line generator lens producing a beam angle of 16° fitted. (RS stock no. 213-3613) is supplied with a line generator lens producing a beam angle of 106° fitted. The lens on the Beta Cameo series cannot be replaced with a line generating lens.
Optical characteristics

<table>
<thead>
<tr>
<th>Parameter</th>
<th>RS stock no./Value</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>RS stock no.</td>
<td>111-348 194-010</td>
<td></td>
</tr>
<tr>
<td>Value</td>
<td>111-352</td>
<td></td>
</tr>
<tr>
<td>Beam size</td>
<td>4.5 x 2.5</td>
<td>mm</td>
</tr>
<tr>
<td>Minimum focus (lens extended)</td>
<td>194-010</td>
<td></td>
</tr>
<tr>
<td>Spot size at minimum focus</td>
<td>111-352</td>
<td></td>
</tr>
<tr>
<td>Polariation ratio</td>
<td>3.5 x 2.5</td>
<td>mm</td>
</tr>
<tr>
<td>Output aperture</td>
<td>80</td>
<td>Micron</td>
</tr>
<tr>
<td>Angular deviation of beam to</td>
<td>50</td>
<td>Micron</td>
</tr>
<tr>
<td>case (front cell)</td>
<td>&lt;5</td>
<td>mRad</td>
</tr>
</tbody>
</table>

The spot size is determined by optical measurement. The relationship of the spot size to illumination is \( \frac{1}{2R^2} \), therefore the size to the human eye will appear bigger.

Mechanical details

Absolute maximum ratings

<table>
<thead>
<tr>
<th>Parameter</th>
<th>RS stock no./Value</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>RS stock no.</td>
<td>111-348 194-010</td>
<td></td>
</tr>
<tr>
<td>Value</td>
<td>111-352</td>
<td></td>
</tr>
<tr>
<td>Supply voltage</td>
<td>4.5至12V</td>
<td></td>
</tr>
<tr>
<td>TTL disable input voltage</td>
<td>-3至+7V</td>
<td></td>
</tr>
<tr>
<td>Operating temperature</td>
<td>-10至+65°C</td>
<td></td>
</tr>
<tr>
<td>Storage temperature</td>
<td>-40至+85°C</td>
<td></td>
</tr>
</tbody>
</table>

Power supplies and earthing

Laser modules which operate from a negative voltage can be run from an unregulated supply within the range of -8 to -12V. By operating at the lower (-8V) end of the power supply range, less heat will be dissipated within the device and hence the expected life will increase.

Laser modules which operate from a positive voltage may only be run from a supply which has been regulated to at least 5%, within the limits specified.

For all laser modules the case is isolated from the supply voltages.

It is advisable for any floating power supplies to have the '0' volts connection (and if used, the heatsink) taken to ground. If this is not done, then in artificially noisy environments, the power supply leads can act as aerials. Under these conditions any noise picked up can damage the laser module. If a heatsink is not used, then the barrel of the laser module should be grounded.

TTL disable

This feature is only available on laser modules which operate from a negative supply voltage.

An input of between +4 and +7V applied to the TTL disable input will turn the laser 'off' and an input of 0V will turn it 'on'. If it is not in use it may be left floating. The laser may be pulsed 'on' and 'off' using this input to a frequency of at least 10Hz.

Heat sink requirements

When operating above their minimum supply voltage and/or at elevated temperatures above 30°C ambient, an additional heat sink must be used. If the case temperature of the embedded laser diode should exceed its maximum specification, premature or even catastrophic failure may occur.

To help dissipate heat from the laser module the following graphs have been provided which show the additional surface area of 2mm thick aluminium plate required by each model when operated from different supply voltages and in different ambient temperatures. It has been assumed that good contact exists between the module and the additional heat sink to ensure low thermal resistance.

For maximum effect position, the heat sink so that it contacts the module just to the rear of the fluted front section (this may require peeling back the label) and use thermally conductive cream between surfaces.
Appendix D PixeLink PL-A741 camera
PixeLINK
PL-A741
MV Camera

The all-in-one digital camera designed with your industrial inspection application in mind.

General Description

The PL-A741 is a high-performance, 1.3 megapixel monochrome camera designed specifically for machine vision applications. Fully IIDC 1.3 (DCAM) compliant, the PL-A741 uses a standard FireWire interface for plug-and-play operation with the host computer. Extended features—such as trigger and general-purpose output controls—add a level of functionality beyond the IIDC standard, providing excellent performance for the price. On-board Flat Field Correction provides image quality similar to high-end CCD cameras.

Easy to Use!

• Compatible: The PL-A741 can be operated right out of the box with any system that supports the FireWire (IEEE 1394) IIDC 1.3 specification. Within minutes, the camera can be controlled by any IIDC compatible software such as National Instruments LabVIEW, and a host of other applications.

• Connectable: The PL-A741 connects to the computer via a single FireWire cable that supplies power to the camera and allows high-speed data communication. No special or expensive frame grabber card is required. The camera’s two FireWire ports allow multiple cameras to be connected together (“daisy chained”) on a single FireWire bus. The external trigger allows cameras to be synchronized with each other or with external systems.

• Controllable: The camera’s rich set of features and capabilities can all be controlled through software. A global shutter and external trigger allow synchronization in demanding machine vision applications.

• Fast: In video mode, the camera can deliver 33 fps at 1k x 1k resolution, 107 fps at VGA resolution (640 x 480), and 8000 fps at 472 x 8, all with a user-definable region of interest (ROI). Full-field-of-view images can be decimated for high-speed transmission.

• Extendable: With the Developer’s Kit, PixeLINK supplies an extensive Application Programming Interface (API) and camera control GUI for fast and easy application development.

Advanced Features Include:

• On-board non-volatile memory for storage of the camera settings. When the camera is shut down, it can be restarted with the same settings even when connected to a different computer.

• Multiple-slope dynamic range controls for balanced image exposure. Reduce overexposure of bright areas while increasing the level of visible detail in dark areas, without losing data in the image, by defining up to three “knee points” in the exposure time.

• Two general-purpose output connections for camera-based control of external equipment such as lighting and filters. The output controls can be software enabled or programmed to respond to an input trigger signal incorporating user-defined delays.

• On-camera, user-programmable lookup table (LUT).

• New features can be added in the field via the FireWire interface.

• Enhanced trigger with delay timings relative to output controls and start of image capture.

• Decimation (ROI sub-sampling) to maintain wide field of view at lower resolutions and high frame-rates.
Features

Sensor
- 2/3" CMOS 1280 x 1024 resolution (8.576 mm x 6.912 mm, 11.01 mm diagonal)
- 6.7 μm square pixels

Frame Rate — Maximum frames per second

<table>
<thead>
<tr>
<th>ROI Size</th>
<th>Rolling Shutter</th>
<th>Global Shutter</th>
</tr>
</thead>
<tbody>
<tr>
<td>1280 x 1024</td>
<td>27</td>
<td>27</td>
</tr>
<tr>
<td>1000 x 1000</td>
<td>34</td>
<td>34</td>
</tr>
<tr>
<td>640 x 480</td>
<td>105</td>
<td>104</td>
</tr>
<tr>
<td>472 x 8</td>
<td>8000</td>
<td>4997</td>
</tr>
<tr>
<td>96 x 8</td>
<td>8000</td>
<td>8000</td>
</tr>
</tbody>
</table>

Performance
- Spectral Range 350 - 1000 nm
- FPN: < 1DN, PRNU: < 1%
- Read Noise 1.9 DN average standard dev.
- Responsivity @ 600nm: 9.4 to 86 DN/(μJ/cm²)
- Dynamic Range: 54.6 dB linear, > 100 dB
- NEE 202 μJ/cm², SEE 118 nJ/(μm²)

Triggering / Strobe / Flash
- S/W or H/W (external) trigger (TTL to 12V)
- Two user-programmable outputs that can be used stand-alone or synchronized to trigger

Controls
- Exposure (0.04 ms to 1 second)
- Shutter - rolling or synchronous
- Gain & Brightness (black level adjust)
- Frame Rate (2 fps to max)
- Trigger & Strobe Modes
- Region of Interest & Decimation (2X)
- Pixel format 8-bit or 10-bit

Other Features
- Programmable LUT
- Extended Dynamic Range
- On-camera configuration memory
- FPN and PRNU correction (gain/offset correction, flat field correction – per pixel)

Compatibility
- IIDC 1.3
- Format 0, Modes 5 and 6
- Format 1, Modes 2, 5, 6 and 7
- Format 2, Modes 2 and 6
- Format 7

Computer Interface
- Two FireWire (IEEE 1394) connectors allow daisy chaining of the camera

Optical Interface
- Standard C-mount 3/4" optics
- BK7 clear glass protective filter

Mechanical Interface
- M3 threaded holes – 4 in front plate around C-mount and 4 in camera base

Trigger Interface
- 6 pin Hirose connector

Power Requirements
- Power supplied over the FireWire bus
- Max consumption - 4.2 W

Size and Weight
- Standard Configuration (PL-A741)
  H x W x L: "1.38" x 1.97" x 3.94"
  (35 mm x 50 mm x 100 mm)
  Weight (without lens): 160 g
- Right Angle (PL-A741-R)
  H x W x L: "1.38" x 1.97" x 5.16"
  (35 mm x 50 mm x 131 mm)
  Weight (without lens): 190 g

Environmental Requirements
- FCC Class B & CE
- Shock – 50 G
- Vibration – 10 G (20 to 200 Hz)
- Temperature – 0°C to 50°C (non-condensing)

Status LED
- Flashing red and green
- Signals indicate idle, operating, warning and failed status
Appendix E Tamron 23FM25SP lens

SPECIFICATIONS

Focal Length
25mm

Iris Range
F/1.4 to 22

Iris Operation
Manual with Lock

Focus Operation
Manual with Lock

Mount
C

1/3" Angle of View
11.0° x 8.2°

1/2" Angle of View
14.6° x 11.0°

2/3" Angle of View
20.0° x 15.1°

Effective Diameter (Front/Rear Lens)
Ø23.5mm/Ø16.5mm

Minimum Object Distance
0.15m

Back Focus
17.17mm (in air)

Filter Size
M30.5 P=0.5

Maximum Diameter
Ø34mm

Overall Length
52.2mm

Weight
103g
Appendix F Goniometer
Appendix G Rodenstock laser profilometer
1.4 Technical Data

Measurement principle: Dynamic focusing of the laser beam, interpretation of lens position or focus error signal

Measurement objects: Flat or curved surfaces with a minimum of 1% reflection (smaller available by order)

Meas. range: ±300 μm, ±30 μm, ±3 μm
Meas. resolution: related to actual range 200 nm, 20 nm, 10 nm
Meas. linearity: related to actual range 0.3 %, 1 %, 3 %

Temperature drift: 0.5 μm/°C
Meas. rate: depends on the degree of variation of surface height. Minimum 5 meas./sec in case of max. variation (-300 μm to +300 μm), normal rate about 500 meas./sec.
Meas. rate in adjust mode: up to 350 kHz
Display: 4 digit LED-Display, indicator string with 9 diodes
Display for exceeded range

Sensor: Infrared laser diode with focus detector. Servo with positioning sensor
Wavelength: 780 nm (infrared)
Power: 0.2 mW
Measuring distance: Depending on sensor 1 mm or 4 mm.
Angle to meas. surface: 90° ±13°, ±7°
Diameter of meas. spot: 2 or 4 μm

Interfaces (Pin assignment: s. p.1-4):
Measuring output: Calibrated analog signal ±10 V at 10 kohm for ±300, ±30 or ±3 μm according to range. Focus signal analog ±10 V at 10 kOhm, reflection intensity 13.6 V at 10 kOhm (=50% reflection), Sensor adjustment signal ±10.5V at 10 kOhm
Digital signal: Reflection low
 Connector for computer: Bus-Extension (Pin assignment: see page 4-1)
Supply Voltage: 110/120/200/240V
Power dissipation: max. 75 W
Environmental conditions:
Operating temperature: +5°C - +48°C
Storage temperature: -20°C - +60°C
Humidity: Max. 96%
Dimensions:
Sensor: 80 x 27 x 43.5 mm.
No. of Control units: 2 3 4
Height: 149 mm 149 mm 149 mm
Width: 225 mm 362 mm 469 mm
Depth: 267 mm 267 mm 267 mm

Weight:
Sensor: 130 g
Control unit: ea. 3.5 kg

Safety class:
Sensor: IP 54
Control Unit: GS - Safety class I, VDE 0411
Appendix H BS EN ISO 11562:1998 (Abridged)
Introduction

This International Standard is a Geometrical Product Specification (GPS) standard and is to be regarded as a General GPS standard (see ISO/TR 14638). It influences chain links 2 and 3 of the chains of standards for roughness profile and waviness profile and chain link 2 of the chain of standards for primary profile and is envisaged also to cover roundness and other form characteristics.

For more detailed information of the relation of this standard to other standards and the GPS matrix model, see Annex B.

For digital instruments, the appropriate filter for surface profile information is a phase correct filter. The chosen weighting function, for the phase correct filter, is Gaussian with a 50 % transmission at the cut-off wavelength. This provides a transmission characteristic with a relatively sharp cut-off.

It is of importance that the transmission for the cut-off wavelength is 50 % since the short wave and long wave portions of the surface profile are separated and can be recombined without altering the surface profile.

1 Scope

This International Standard specifies the metrological characteristics of phase correct filters for the measurement of surface profiles. In particular it specifies how to separate the long and short wave content of a surface profile.

2 Definitions

For the purposes of this International Standard, the following definitions apply.

2.1 profile filter
Filter which separates profiles into longwave and shortwave components.

2.1.1 phase correct profile filter
Profile filter which does not cause phase shifts which lead to asymmetrical profile distortions

2.2 phase correct filter mean line (mean line)
Long wave profile component which is determined for any point of the profile by a weighted mean value derived from adjacent points

2.3 transmission characteristic of a filter
Characteristic which indicates the amount by which the amplitude of a sinusoidal profile is attenuated as a function of its wavelength

2.4 weighting function
Function for calculating the mean line which indicates for each point the weight attached by the profile in the neighbourhood of that point

NOTE The transmission characteristic of the mean line is the Fourier transformation of the weighting function.

2.5 cut-off wavelength of the phase correct filter
Wavelength of a sinusoidal profile of which 50 % of the amplitude is transmitted by the profile filter

NOTE Profile filters are identified by their cut-off wavelength value.

2.6 transmission band for profiles
Band of sinusoidal profile wavelengths which are transmitted at more than 50 % when two phase correct filters of different cut-off wavelengths are applied to the profile

NOTE The profile filter with the shorter cut-off wavelength retains the long wave profile component and the profile filter with the longer cut-off wavelength retains the short wave profile component.

2.7 cut-off ratio
Ratio of the long wavelength characteristic cut-off to the short wavelength characteristic cut-off of a given transmission band

3 Characteristics of phase correct profile filters

3.1 Weighting function for the phase correct profile filter
The weighting function of the phase correct filter (see Figure 1) corresponds to the equation of the Gaussian density function. With the cut-off wavelength \( \lambda_{co} \) (where \( \lambda_{co} = \text{cut-off} \)), the equation is as follows:

\[
\psi(x) = \frac{1}{2\pi \lambda_{co}} e^{-\frac{x^2}{2\lambda_{co}^2}} \quad \text{...(1)}
\]

where

- \( x \) is the position in relation to the centre of the weighting function;
- \( \lambda_{co} \) is the cut-off wavelength of the profile filter,

\[
\lambda_{co} = \frac{\lambda_{co}}{\pi} = 0.4697 \quad \text{...(2)}
\]
3.2 Transmission characteristic

3.2.1 Transmission characteristic of the long wave profile component (mean line)

The filter characteristic (see Figure 2) is determined from the weighting function by means of the Fourier transformation. The filter characteristic for the mean line corresponds to the following equation:

\[
\frac{a_1}{a_0} = e^{-\left(\frac{a \lambda}{\lambda_0}\right)^2}
\]

... (3)

where

- \(a_0\) is the amplitude of sine wave roughness profile before filtering;
- \(a_1\) is the amplitude of this sine profile in the mean line;
- \(\lambda_0\) is the limiting wavelength of the profile filter;
- \(\lambda\) is the wavelength of the sine profile.

3.2.2 Transmission characteristic of the short wave profile component

The short wave profile component is the difference between the surface profile and the long wave profile component. The equation as a function of the limiting wavelength \(\lambda_0\) is:

\[
\frac{a_2}{a_0} = 1 - e^{-\left(\frac{a \lambda}{\lambda_0}\right)^2}; \quad \frac{a_2}{a_0} = 1 - \frac{a_1}{a_0}
\]

... (4)

where \(a_2\) is the amplitude of the sine wave roughness profile.

4 Limits of error of phase correct filters

For phase correct filters no tolerance values are given. Instead of tolerances, a graphical representation of the deviations of the realized phase correct filter from the Gaussian filter shall be given as a percentage value over the wavelength range 0,01 \(\lambda_0\) to 100 \(\lambda_0\). An example of a deviation curve is given in Figure 4.
Figure 2 — Transmission characteristic of the long wave profile component
Figure 3 — Transmission characteristic for the short wave profile component

Figure 4 — Example of a deviation curve of a realized phase correct filter from the Gaussian filter
Appendix I Images for the example in Section 6.4.6

The images below have had useless portions cropped off. However, the longitudinal FOV remains, which is 40 mm. The wood species is beech. The sample is B2.5.

Fig. I-1 Shadow image L1

Fig. I-2 Shadow image L2

Fig. I-3 Shadow image R1

Fig. I-4 Shadow image R2
Appendix J Images for Section 7.9.2

The FOV of the images is 20×16 mm. The wood species is Oak. The sample is O2.

Fig. J-1 Angle of misalignment = 0

Fig. J-2 Angle of misalignment = 1°
Fig. J-3 Angle of misalignment = 2°

Fig. J-4 Angle of misalignment = 3°
Fig. J-5 Angle of misalignment = 4°

Fig. J-6 Angle of misalignment = 5°
Appendix K Machining parameters for the samples in Chapter 8

The table below records the machining parameters for the samples in Chapter 8. Spindle speed is the actual value measured during the cutting process. Feed rate is the value set up by the PC program. Calculated pitch and height are the values calculated with the spindle speed and the feed rate by using Eq. 1-1 and Eq. 1-2. There are two knives on the cutterhead, but one of the knives is mounted higher than the other one. So, effectively, there is only one knife cutting, and the cutting radius is approximately 60 mm.

The planer can be programmed to simulate 4-knife cutting process, and spindle vertical vibration can be stimulated controllably via the piezo-actuators during the cutting process. The vibration is meant to make cutter mark defects on the surface. The stimulated spindle vertical vibration is defined by a vector, such as [0 4 0 -4]. The 4 elements in the vector stand for 4 vertical displacements of the spindle off the centre when the knife cuts the sample in 4 consecutive sessions. Note that vibration [0 0 0 0] means that the piezo-actuators and their amplifiers are switched on, but no vibration is intentionally stimulated. In this circumstance, however, there may still be some kinds of vibration, such as that due to inappropriate clamping of the sample.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Spindle speed (rpm)</th>
<th>Feed rate (mm/s)</th>
<th>Calculated pitch (mm)</th>
<th>Calculated height (µm)</th>
<th>Depth of cut (µm)</th>
<th>Stimulated spindle vertical vibration (µm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>B2 5</td>
<td>1100</td>
<td>50</td>
<td>2.73</td>
<td>15.5</td>
<td>100</td>
<td>[0 4 0 -4]</td>
</tr>
<tr>
<td>B2</td>
<td>1225</td>
<td>40</td>
<td>1.96</td>
<td>8.0</td>
<td>100</td>
<td>[0 0 0 0]</td>
</tr>
<tr>
<td>B1 5</td>
<td>1210</td>
<td>30</td>
<td>1.49</td>
<td>4.6</td>
<td>50</td>
<td>[0 0 0 0]</td>
</tr>
<tr>
<td>R2 5</td>
<td>1198</td>
<td>50</td>
<td>2.50</td>
<td>13.1</td>
<td>100</td>
<td>[0 4 0 -4]</td>
</tr>
<tr>
<td>R2</td>
<td>1223</td>
<td>40</td>
<td>1.96</td>
<td>8.0</td>
<td>100</td>
<td>[0 3 0 -3]</td>
</tr>
<tr>
<td>R1 5</td>
<td>1155</td>
<td>30</td>
<td>1.56</td>
<td>5.1</td>
<td>50</td>
<td>[0 1 5 0 -1 5]</td>
</tr>
<tr>
<td>O2 5</td>
<td>1220</td>
<td>50</td>
<td>2.46</td>
<td>12.6</td>
<td>100</td>
<td>[0 4 0 -4]</td>
</tr>
<tr>
<td>O2</td>
<td>1240</td>
<td>40</td>
<td>1.94</td>
<td>7.8</td>
<td>100</td>
<td>[0 0 0 0]</td>
</tr>
<tr>
<td>O1 5</td>
<td>1213</td>
<td>30</td>
<td>1.48</td>
<td>4.6</td>
<td>50</td>
<td>[0 0 0 0]</td>
</tr>
</tbody>
</table>
Appendix L Publications

- Inspection of Wood Surface Waviness Defects Using The Light Sectioning Method, accepted for Proceedings of the Institution of Mechanical Engineers Part I Journal of Systems and Control Engineering
Inspection of wood surface waviness defects using the light sectioning method

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The manuscript was received on 30 June 2005 and was accepted after revision for publication on 26 May 2006

Abstract: Surface waviness variations are a major type of defect on planed wood products. A number of methods have been investigated for the inspection of waviness defects on wood surfaces. This paper describes a new implementation of the light sectioning method with the latest structured lighting and machine vision techniques for this purpose. As a reference, a laser profilometer is used. The data from the light sectioning method and from the profilometer are highly correlated.

Keywords: wood surface, waviness defect, light sectioning, machine vision, structured lighting

1 INTRODUCTION

Planing is a major machining process used in the wood working industry. As illustrated in Fig 1, the principle of the planing process is very similar to that of the up-milling process in the metal working industry. However, the cutting tool up velocities and the feed speeds, typically within the range 30-125 m/s and 5-120 m/min [1] respectively, are much higher than those in the metal working industry. In references [2] and [3], even a feed speed of 200 m/min is quoted. Due to the kinematics of the planing process, cutter marks will inevitably be left on the machined surface. However, cutter marks, also termed as waviness in the wood working industry, are actually not defects provided they are small and uniform in width and height. In reality, due to various reasons, such as different rotating radius of cutters on a cutterhead, oscillation of the cutterhead’s spindle, and weak structure of machines and so on, the widths and heights of cutter marks on a planed surface are sometimes inconsistent, as shown in Fig 1. These inconsistencies are known as waviness defects.

2 LITERATURE REVIEW

For the assessment of waviness defects on wood surfaces, a number of methods have been investigated. In general, these methods are classified into two categories: contact method and non-contact methods.

2.1 Contact method

The contact method is always in the form of a stylus tracer. In this method, a stylus is driven across the surface to be measured and surface profiles are produced by recording the vertical movement of the stylus due to the surface height variations and its traverse movement along the surface.

There is a selection of general-purpose stylus-tracing instruments available on the market, but they are mainly developed for metal surfaces. Peters and Mergen [4], Faust [5], and Jackson [6] developed wood-specific stylus tracing instruments.
The problems with stylus tracing on wood surfaces were studied in references [6] and [7] and reviewed in reference [8]. One of the major problems is that the stylus, usually made of metal, tends to deform the surface being measured, consequently introducing errors. Another major problem is that the stylus-tracing technique can only be implemented at a slow speed in order to avoid bouncing (losing contact with the surface). Peters and Mergen [4] and Faust [5] reported 7.5 mm/min, while Jackson et al. [1] did 0.2 mm/s. Clearly, this level of measuring speed makes this technique unsuitable for online applications.

2.2 Non-contact methods

The most widely investigated non-contact methods for measuring wood surfaces are optical methods. They can be further classified into three methods according to their respective principles:

(a) Triangulation sensing
(b) Shadow analysis
(c) Light sectioning

The triangulation sensing method has been investigated for wood surfaces in references [8] to [12] and for metal surfaces in references [13] to [15]. The principles and some in-depth discussions about this technique can be found in references [16] and [17]. There are some commercial triangulation sensors on the market, such as those from MICROEPSILON (www.micro-epsilon.com) and Keyence (www.keyence.com), although these sensors may be named differently. Potentially, triangulation sensors can measure the surface height with resolution down to 0.1 μm or even better [16, 17], but they are always quite expensive when high resolution and high accuracy are required. Similar to stylus tracers, triangulation sensors need to scan the surface to produce surface profiles.

There is another technique, known as autofocus, for measuring profiles of generic surfaces. Because no reference to its applications on wood surfaces has been found, this technique is not introduced here. Later in this paper, however, an autofocus-based device, referred to as a laser profilometer, is used to produce reference surface profiles, and the technique will be briefly introduced there.

Equipment using triangulation sensors or autofocus sensors to measure surface quality is sometimes referred to as an optical profilometer. In fact, the optical profilometer is similar to the stylus profilometer in many aspects. The major difference is that the optical profilometer uses a non-contact 'optical stylus', while the stylus profilometer uses a contact stylus.

The shadow analysis method is used to assess surface waviness by analysing the shadows on the surface illuminated by oblique light along the lay, i.e. the feed direction. Hesselbach [3] and Hoffmeister and Grubler [2] used this method to measure cutter mark widths. Maycock [18] used a similar approach to analyse cutter mark variations in the frequency domain. This method was also used in the assessment of wood surface roughness [5]. In general, the shadow analysis method cannot measure surface heights.

The light sectioning method also requires oblique illumination. In this approach, a light stripe is projected from the side of the sample on to the surface to produce a light section. As illustrated in Fig. 2, the light section is actually a wavy line produced by the projected light due to the wavy nature of the surface. Furthermore, as illustrated in Fig. 3, there is a triangular relationship between the height of a cutter mark wave H and the height of its corresponding wave L in the light section, which is \( H = L \tan \theta \), or \( L = H / \tan \theta \), where \( \theta \) is the angle of incidence of the projected light with respect to the surface.

![Fig. 1 The schematic of the planing process and the cutter mark parameters](image)

![Fig. 2 The principle of light sectioning](image)
Inspection of wood surface waviness defects

Therefore, by measuring the wavy line, i.e., the light section, the widths and heights of cutter mark waves on the surface can be calculated.

The light sectioning method is not a new method. The studies on assessing wood surfaces using this approach can be dated back to half a century ago. It is reported in reference [5] that Lutz used this approach to obtain a profile from a wood surface in 1952. In reference [19], it is reported that the Swedish Forest Products Laboratory devised a light sectioning system in 1951 using the same principle, and some sample light sections obtained from the approach are also shown in the reference. Elmendorf and Vaughan also reported a similar technique in 1958 [7]. Since the early 1960s, however, there has not been further research reported. The above-mentioned research may be different from one another in some aspects, but they all used a microscope to magnify the light sections. As a result, the sampling length could not be long. Marian in reference [19] suggested a sampling length of 1 mm; Marian believed that "This sampling length is usually too small to be representative of the surface to be tested." Therefore, it may be reasonably assumed that the light sectioning method could not produce significant results in those days.

However, the light sectioning method has long been successfully applied in some other industrial applications such as inspecting automotive parts [20, 21]. The difference between those applications and measuring cutter marks on wood surfaces is that the latter may require higher resolution. However, considering the state of the art of the machine vision technologies, the light sectioning method may well provide quantitative analysis of machined wood surface quality.

Compared to the triangulation sensors, this method potentially has a higher measuring rate as it does not need scanning of the surface. Compared to the shadow analysis method, especially the technique developed in references [2] and [3], the light sectioning method is potentially able to measure cutter mark heights.

3 EXPERIMENTAL SET-UP

According to the principles of the light sectioning method discussed above, a test rig was constructed. As illustrated in Fig. 4, a light source projects a light stripe in a fan from the side of the wood sample. The projected light stripe creates a light section on the sample according to the shape of the surface. The light section, parallel to the feed direction on the surface, is captured by a camera, which is connected to a personal computer (DC).

The light source used in the test rig is a laser line generator. This laser features a patented Powell glass lens designed to generate lines without a Gaussian profile. Normally, the line generated by an ordinary laser line generator has a Gaussian intensity profile along the length of the line. A comparison of intensity profiles produced by a Gaussian line generator and a non-Gaussian line generator is shown in Fig. 5. Clearly, non-Gaussian line generators will benefit the light sectioning method.

The laser was positioned so that the light came in at a small angle to the sample surface. Due to the triangular relationship shown in Fig. 3, this angle has a predominant influence on $L$, i.e., the heights of the waves in the light section. When the angle $\theta$ is smaller than 6°, the ratio of $L$ to $H$ will be greater than 10, which is essentially magnifying the heights of the cutter marks. Clearly, the smaller the angle, the greater the magnification. However, if the angle is too small, the light section will appear broken and

*Refer to http://www.stockeryale.com/lasers/advantages.htm for more information.*
blurred in the image, which makes the subsequent image processing difficult. The image in Fig 6 is such an example, which was taken with an angle slightly smaller than 1°. Based on the experiments, the angle of incidence was set to between 1.5° and 6°.

The camera used is a monochrome complementary metal oxide semiconductor (CMOS) camera. The resolution of the camera is up to 1280 x 1024, and the CMOS sensor size is 2/3 inch. The lens on the camera is a 100 mm lens.

The computer used in the testing is a Celeron® 466 PC with 128 Mb memory. The operating system of the PC is Microsoft Windows 2000 Professional. The image processing software is MATLAB Image Processing Toolbox.

4 RESULTS AND ANALYSIS

4.1 Analysis of a light section

A number of images were taken from the testing described above, one of them is shown in Fig. 7. Note that the image in Fig. 7 is only the useful portion of the original image, with those regions only in black removed so that the image is not in the aspect ratio of 5 to 4. The image was taken in the following conditions.

Object distance: 565 mm
Field of view: 22.5 x 18 mm
Image resolution: 1280 x 1024
Angle of incidence of the laser stripe: 5.7°
Lens f-number: 3.5
Exposure time: 72 ms

After applying an edge-finding algorithm to the image in Fig. 7, a profile was obtained as plotted in Fig. 8. Note that the profile in Fig. 8 has had the least squares mean line removed. Clearly, this profile encompasses both the surface waviness and surface roughness.

In order to extract the surface waviness, a low-pass filter has to be applied. There are a number of filter models, such as the sliding average filter, 2CR filter, Gaussian filter, etc. Among them, the Gaussian filter has good roll-off capability and introduces low distortion and phase shift to the data [22]. The Gaussian filter has already been specified as a standard in the metrology industry by the
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International Standardization Organization (ISO) in ISO 11562 [23] Essentially, the kernel of the Gaussian filter is a weighting function, which has the shape of a Gaussian density function and is mathematically described by the equation below

\[ g(x) = \frac{1}{a\lambda_c} \exp \left[ -\pi \left( \frac{x}{a\lambda_c} \right)^2 \right] \]  

with \( x \) being the distance from the centre of the weighting function, \( \lambda_c \) the cut-off wavelength of the filter, and \( a \) a constant, defined by

\[ a = \sqrt{\frac{\log 2}{\pi}} = 0.4697 \]  

Due to the value of \( a \), the Gaussian filter is defined to have a transmission of 50 per cent at the cut-off wavelength \( \lambda_c \).

A Gaussian filter with a cut-off wavelength of 1.4 mm is applied to the profile shown in Fig. 8, and the resultant profile is plotted in Fig. 9. In addition, local maximums and local minimums on the filtered profile are marked on the plot.

4.2 Comparison with a reference

In order to assess the performance of the light sectioning method, a profilometer was used as a reference. The profilometer is an autofocusing device. The principle of it is to focus a laser spot on the surface being measured and detect the light scattered from a surface with a focus detector, if the focus is lost due to the surface height variations, then the focus detector generates a signal to refocus the lens; while the lens is being refocused, an inductive displacement transducer measures the lens displacement, lens displacements are recorded while the sample moves under the laser so that the surface contour is measured. There is more information on this profilometer available in reference [24].

The vertical resolution of the profilometer is 20 nm while the horizontal resolution, i.e. the distance the sample moves per step, is selectable, and was set to 25 \( \mu \)m. Since this profilometer also needs to scan the surface, it is time-consuming to measure a surface with it.

A profile obtained from the profilometer is plotted in Fig. 10. Similarly, this profile has also had the least squares mean line removed. After applying a Gaussian filter with the same cut-off wavelength of 1.4 mm, a filtered profile is obtained and plotted in Fig. 11, the local maximums and local minimums are also marked on the profile. Since the profilometer uses a laser, the profile is referred to as the laser profile in the following text.

In order to compare the light section profile and the laser profile, both profiles are normalized with the following procedures. Re-sample the laser profile with the sampling number of the light section profile, making both profiles have the same scale in the \( x \) axis. Convert both profiles using the following:

![Fig. 8 The profile obtained from the light section shown in Fig. 7](image-url)
equation, making both of them have the same scale in the $y$ axis

$$y = \frac{y_0}{\max(y_0) - \min(y_0)} \quad (3)$$

where $y_0$ is the original profile and $y$ is the normalized profile.

After normalization, the light section profile and the laser profile are plotted together in Fig. 12. It can be seen that the light section profile and the laser profile are similar to a large extent. The correlation coefficient of the two profiles is 0.89, calculated by

$$\text{corr}(A, B) = \frac{\sum_m (A_m - \bar{A})(B_m - \bar{B})}{\sqrt{\sum_m (A_m - \bar{A})^2} \sqrt{\sum_m (B_m - \bar{B})^2}} \quad (4)$$
where

\[ A = \text{normalized light section profile and } \bar{A} = \frac{\sum A_m}{m} \]
\[ B = \text{normalized laser profile and } \bar{B} = \frac{\sum B_m}{m} \]
\[ m = \text{sampling number of } A \text{ and } B \]

5 DISCUSSION

The ultimate purpose of this research is to find out a method for online inspection of waviness defects on wood surfaces. As the first step, this paper investigates the feasibility of applying the light sectioning method on static wood samples. Future work will be focused on moving samples. Clearly, moving samples will have blurring problems. However, according to the authors' experience, as long as the exposure time is short enough and a strobe light is used, the blurring will be limited to a small extent. Besides, deblurring algorithms can be helpful.

In the experimental set-up shown in Fig 4, the laser stripe is supposed to be projected parallel to the feed direction. In reality, however, it is impossible.

*In a previous project [25], a blur of 1/1000 of the FOV (field of view) was obtained from an object moving at a speed of 3 m/s
to guarantee this set-up. If the light stripe is not projected parallel to the feed direction, the light section will appear inclined in the image, as illustrated in Fig. 13(b). Figure 13(a) shows a perfectly aligned light section. The vertical lines in Fig. 13 represent the peaks of the cutter marks on the surface. (Here and in the following text, the camera is assumed to be aligned to the surface so that the feed direction of the surface is parallel to one dimension of the FOV of the camera.) Nevertheless, the inclination can be removed by removal of the least squares mean line of the light section. Considering just this point, the light section profile in Fig 9 has the least squares mean line removed.

In order to study further the effects of misalignment of light sections, a misaligned light section was simulated. In Fig 14(a), a cutter mark wave in a light section with 5° of misalignment is plotted (dashed line) alongside the cutter mark wave with the least squares removed (solid line). In Fig 14(b), the same cutter mark wave in the same light section with no misalignment is plotted. The simulated cutter mark is 2 mm wide with a cutting radius of 60 mm, and the angle of incidence of the laser stripe is 7° with respect to the surface. Comparison of the curves in Fig 14(a) and (b) shows that after removing the least squares mean line, the misaligned light section is almost the same as the perfectly aligned light section. In fact, there is a small difference between the two curves. However, the difference is only in the order of a fraction of a micrometer, which can be ignored compared to the amplitude of the curves. Another simulation with 10° of misalignment shows the difference is no more than 1 μm. Further simulations with different cutter mark widths show similar results. Therefore, it is concluded that misalignment of light sections can be acceptably corrected by removing the least squares of the misaligned light section when the angle of misalignment is not too large. Moreover, according to empirical observations, a misalignment larger than 5° is easy to discern with the eye.

Fig. 13 Misalignment of the light section

Fig. 14 Simulated effects of removal of the least squares of a misaligned light section
6 CONCLUSIONS

Waviness defects, in the form of width and height variations of cutter marks on planed wood surfaces, are a major type of surface defect in the wood working industry. A number of methods have been investigated before. This research is based on the light sectioning method, which has not been fully investigated in the wood working industry. Since it was first studied nearly half a century ago. With the help of the latest machine vision techniques, the light sectioning method has proved in this research to be a feasible solution to the inspection of waviness defects on wood surfaces. More importantly, the light sectioning method can potentially be applied in production lines due to its high data rates and non-contact approach.

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REFERENCES

2 Hoffmeister, H. W. and Grubler, T. In-process measurement of the cut width on planed massive wood surfaces, 1999
5 Faust, T. D. Real time measurement of veneer surface roughness by image analysis Forest Products J, 1987, 37(6), 34–40
10 Lemaster, R. L. and Beall, E. C. The use of an optical profilometer to measure surface roughness in medium density fiberboard Forest Products J, 1996, 46(11/12), 73–78
13 Costa, M. E. M. Surface inspection by an optical triangulation method Opt Engng, 1996, 35(9), 2743–2747
19 Marian, J. E. Surface texture In Adhesion and adhesives, 1967, pp 69–86 (Elsevier)
20 Strand, T. G. Optical three-dimensional sensing for machine vision Opt Engng, 1985, 24(1), 33–40
21 Pastorius, W. Machine vision for industrial inspection metrology and guidance In Fourth Annual Canadian Programmable Control and Automation Technology Conference and Exhibition, 1998, paper 13A2-1/1-5
22 Exploring surface texture, 2003 (Taylor Hobson Limited)
24 Griffiths, B. Manufacturing surface technology surface integrity and functional performance, 2001 (Penton, London)
APPENDIX

Notation

\[
\begin{align*}
g(x) & \quad \text{Gaussian filter kernel} \\
H & \quad \text{cutter mark height (mm)} \\
L & \quad \text{light section wave height (mm)} \\
W & \quad \text{cutter mark width (mm)} \\
x & \quad \text{distance from the centre of the Gaussian filter kernel (mm)} \\
\alpha & \quad \text{constant in the Gaussian filter kernel function} \\
\theta & \quad \text{angle between the incident light and the surface plane} \\
\lambda_c & \quad \text{filter cut-off wavelength (mm)}
\end{align*}
\]
Measuring cutter marks on wood surfaces with machine vision techniques

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Abstract

Cutter marks are produced on wood surfaces in the planing and moulding processes. Also termed as waviness, cutter marks are medium wavelength surface height variations. This paper reviews the methods that have been investigated for measuring cutter marks on wood surfaces first, and then presents the relevant researches that have been carried out in the Mechatronics Research Centre at Loughborough University. The researches include the light sectioning method and the shadow analysis method.

Keywords. cutter marks, waviness, light sectioning, shadow analysis

1. Introduction

In the modern woodworking industry, it becomes essential to assess the machined surface quality. One of the most important quality characteristics to assess is regarding cutter marks. Cutter marks, also termed as waviness from the standpoint of metrology, are medium-wavelength surface height variations produced in the planing and moulding processes. Figure 1 illustrates the formation of cutter marks on wood surfaces. Note that the cutting tool tip velocities of 30-125 m/s and the feed rates of 5-120 m/min shown in Fig 1 are typical speeds in the wood working industry [1]. The typical widths and heights of cutter marks are 1 – 3 mm and 2 – 18 μm respectively for cutters with a rotating radius of 63 mm.

Due to various reasons, such as different rotating radii of cutters on a cutterhead, oscillation of the cutterhead’s spindle, and weak structure of machines and so on, the widths and heights of cutter marks on a planed or moulded surface are sometimes inconsistent. These inconsistencies are known as waviness defects. More detailed discussions on waviness defects can be found in refs [1, 2].

![Diagram of cutter marks formation](image)

The widths and heights of the cutter marks are inconsistent

Fig. 1 The schematic of formation of cutter marks on wood surfaces
In addition to waviness on machined wood surfaces, there are also short wavelength surface height variations, termed as roughness, and long wavelength variations, termed as forms.

This paper reviews the methods for assessing wood surface roughness and waviness in the first part, and then presents the investigations on this subject that have been carried out in the Mechatronics Research Centre at Loughborough University.

2. Literature review

In order to measure the cutter marks, a number of methods have been investigated. The stylus tracing is a traditional contact method. Applying stylus tracers on wood surfaces have been investigated in refs [2-8]. The problems of this method are discussed in refs [1-3]. Simply speaking, a contact method tends to deform the wood surface and have a lower data rate.

Another widely investigated method is the triangulation sensing method. The principle of this method is illustrated in Fig. 2. A laser projects a laser spot on the surface. The light reflected from the surface is captured by a detector through an imaging lens. As shown in Fig. 2, the surface height will affect the position that the reflected light is captured on the detector. Therefore, the surface height can be derived from the output of the detector.

![Diagram of triangulation sensing method](image)

Fig. 2 The schematic of the triangulation sensing method

With the same principle illustrated in Fig. 2, a Position Sensitive Detector (PSD) is used in refs [9-15], while a Laser Displacement Sensor (LDS) is used in refs [16, 17]. The PSD and the LDS are commercial products that house the light source and the detector in a compact enclosure. In contrast, this method can also be implemented with the light source and the detector separate, such as in refs [14, 18]. In this case, the detector is always a camera.

There is a similarity between the stylus tracing method and the triangulation method: both need scanning across the surface to produce 2-D profiles of the surface. A 2-D profile is very likely to misrepresent a 3-D surface. Averaging multiple surface profiles may improve these profile-based methods, but clearly that will take more time. From this point of view, image-based methods have advantages over the profile-based methods.

Faust [19] and Zhao [20] used images taken from obliquely illuminated wood surfaces to evaluate the surface roughness. Hoffmeister et al. [21] and Hesselbach [22] measured cutter marks on machined wood surfaces by image analysis. Note that Hoffmeister et al. and Hesselbach only measured the widths of cutter marks. The common principle among these researches is that they all utilise the shadows cast on the surface by oblique illumination to extract the surface information. Since the shadow is the key, these methods are referred to as the shadow analysis method in this paper.

The approach developed by Maycock in refs [23, 24] is similar to the shadow analysis method in a sense that oblique illumination was used. However, a photodetector was utilised rather than a camera. Since the
pixels on the photodetector are fabricated in a line, the photodetector can only take a profile of the surface. From this point of view, Maycock's method is a profile-based method.

3. Novel research

Researches carried out on this subject in the Mechatronics Research Centre at Loughborough University include the Light Sectioning method and the Shadow Analysis method.

3.1 The light sectioning method

The principle of the light sectioning method is illustrated in Fig. 3. A light stripe is projected onto the surface, and a camera is put normal to the surface. The projected light on the surface is termed as a light section. Due to the waves (cutter marks) on the surface, the light section is in the form of a wavy line. There is a triangulation relationship shown in Fig. 3 (b).

\[ H = L \cdot \tan \theta \]

Eq 1

where

- \( H \) is the height of a wave on the surface
- \( L \) is the height of the corresponding wave in the light section
- \( \theta \) is the angle of incidence between the light and the surface

The light sectioning method is not a new concept. It has been investigated in refs [4, 8, 25, 26]. However, due to the technical limitations at the time when these researches were being carried out, wood samples were always put under a microscope, and images of which were taken with film cameras. The sample lengths in these researches were very short. In ref [25], a sample length of 1 mm was reported.

Fig 3 (a) The schematic of the light sectioning method (b) A side view of the light sectioning method
The challenge of applying the light sectioning method to measuring surface waviness (cutter marks) on wood surfaces is that the amplitude of wood surface waviness is only about 2 - 20 μm. In contrast, the surface roughness may have larger amplitudes due to the cellular nature of wood [1]. Therefore, separation of waviness from roughness should be implemented carefully.

Figure 4 is a light section image taken with a machine vision camera fixed normal to the surface. The angle of incidence of the light (as illustrated in Fig. 3 (b)) is 57° with respect to the surface. The field of view of the image is 22.5x18 mm. After applying an edge-finding algorithm, a surface profile is extracted from the light section shown in Fig. 4. Then a Gaussian low pass filter is applied to the surface profile to remove the influence of surface roughness. The Gaussian low pass filter is recommended by ISO in [27]. The filtered surface profile is plotted in Fig. 5. Note that the units in Fig. 5 are pixels. By calibration of the imaging system, the surface profile can be easily converted into a metric system.

In order to assess the result of the light sectioning method, the profile in Fig. 5 is compared with a profile measured with a laser profilometer. The comparison gives a high correlation coefficient of 0.89 between these two profiles.

Compared with the stylus tracing and the triangulation sensing method, the light sectioning method clearly has higher data rates. A surface profile can be extracted from just a single image of the surface. If multiple parallel light stripes are projected onto the surface, then several surface profiles can be extracted from a single image.

However, the light sectioning method is still a profile-based method; therefore, the surface profile measured with this method may not precisely represent the real surface. Even if averaging multiple light section profiles can improve the performance of this method, the number of light sections that can be reasonably produced on a surface with the current lighting technology is only 9 light sections at the most. From this point of view, image-based methods such as the shadow analysis method can potentially measure...
the cutter marks on wood surfaces better, as there is more information in an image than in a profile or several profiles

3.2 The shadow analysis method

The shadow analysis method is illustrated in Fig 6. Light is shone along the lay onto the surface at an angle small enough to make the peaks of cutter marks cast shadows on the surface. Since the cutter marks are periodic, the shadows are also periodic.

![Front View](image)

![Top View](image)

Fig 6 The schematic of the shadow analysis method

Hoffmeister et al [21] and Hesselbach [22] measured the widths of cutter marks by analysis of the shadows on the surface. The procedures used by them are:

1. Taking an image of the surface illuminated with oblique light. See Fig 7.
2. Summing up the intensity values of the pixels in the image column by column. This will give an intensity distribution profile of the image.
3. Picking out the peaks on the intensity distribution profile. These peaks are assumed in [21, 22] to correspond to the peaks of the cutter marks on the surface.

For Step 2 in the procedures, there is an important argument. As seen in Fig 7, apart from periodic intensity variations along the row dimension, the intensity also varies randomly due to the natural characteristics of wood such as year rings and cracks, and some man-made scratches. In theory, the intensity variations due to the random reasons will compromise the ‘adding column by column’ algorithm. However, since the intensity variations due to these reasons are random, they cannot make too much difference to the intensity profile calculated in Step 2 due to the summing of many pixels column-wise [21, 22].
According to the algorithm mentioned above, the intensity values in Fig. 7 are summed up column by column, and the peaks on the resultant profile are picked out. The result is plotted in Fig. 8. Note that the intensity distribution profile in Fig. 8 has been smoothed with a low-pass filter in order to make the peak-picking easier. The peaks on the profile are marked with 'x'.

It can be seen that the intensity distribution profile has higher values on the right hand side than on the left hand side generally. This is because the light source was put on the right hand side of the sample when the image was taken. However, since only x-axis positions of the peaks are relevant, this uneven illumination is considered harmless.

The assumption that the peaks of cutter marks correspond to the peaks on the intensity distribution profile was not clearly proved in refs [21, 22]. Different from this assumption, we propose that the peaks of cutter marks should correspond to the quickest change of intensities on the profile in Fig. 8. Therefore, the first derivative of the profile in Fig. 8 was calculated and plotted in Fig. 9. Since the light in Fig. 7 comes from the right hand side, and the origin of the image is on the upper-left corner, the peaks on the profile in Fig. 9 correspond to the peaks of cutter marks on the surface according to the new assumption. (If the light in Fig. 7 comes from the left hand side, then the valleys on the profile in Fig. 9 will correspond to the peaks of cutter marks.)

In order to compare the two assumptions, imaginary lines corresponding to the x-axis positions of the peaks in Fig. 8 and Fig. 9 are superimposed on the original image in Fig. 7, and the new images are shown in Fig. 10 and Fig. 11.

It appears that the superimposed image with the new assumption (Fig. 11) is more consistent with the inspection by the eye. Testing on some more samples with these two assumptions gave the same perception. Therefore, it is concluded that the locations of the peaks of cutter marks calculated with the new assumption are more consistent with the inspection by the eye. However, comparison of the distances between neighbouring peaks in Fig. 8 and Fig. 9, which are actually the widths of the cutter marks, shows that the differences are only in a few pixels. Again, testing on more samples gave the similar result. Therefore, it is
Fig. 8 Intensity distribution obtained with the 'adding column by column' algorithm

Fig. 9 The first derivative of the intensity distribution
also concluded that the new assumption does not change the measurement of the widths of cutter marks very much.
4. Conclusions

In order to measure cutter marks on wood surfaces, various methods have been investigated. The light sectioning method reported in this paper is a new implementation of the method. With the help of the latest machine vision technology, the light sectioning method is proved to be able to measure cutter marks on wood surfaces. The shadow analysis method can be used to measure the widths of cutter marks. A new assumption is made for the shadow analysis method that the peaks of cutter marks on a surface correspond to the quickest change of intensities on the intensity distribution profile of the surface image. However, experimental work shows that the assumption does not change the measurement of the widths of cutter marks very much, although the peaks of cutter marks located with the assumption are more consistent with the inspection by the eye.

References

20 Zhao, X. Inspecting wood surface roughness using computer vision. in Optics in Agriculture, Forestry, and Biological Processing 1995 SPIE
21 Hoffmeister, H W and T. Grubler, In-process measurement of the cut width on planed massive wood surfaces 1999
22 Hesselbach, J, Objective regulation of joint-interval by measurement of the knife impact width 2000, Institute for machine tools and manufacture technique, Technical University of Braunschweig
27 ISO 11562 1996 Geometric Products Specifications (GPS) - Surface Texture Profile method - Metrological characteristics of phase correct filters